Review of Experimental Work in Biomimetic Foils

Michael S. Triantafyllou, Alexandra H. Techet, and Franz S. Hover

Abstract—**Significant progress has been made in understanding some of the basic mechanisms of force production and flow manipulation in oscillating foils for underwater use; a complete mapping of all pertinent principles has not been achieved, however. Conditions for achieving high efficiency, or high lift to drag ratio have only partially been established, for example, while the issue of cavitation is largely unknown. Also, biomimetic observations show that there is a lot more to be learned, since many of the functions and details of fish fins remain unexplored.**

This review focuses primarily on experimental studies on some of the, at least partially-understood, mechanisms, which include:

1. **The formation of streets of vortices around and behind two- and three-dimensional propulsive oscillating foils.**
2. **The formation of vortical structures around and behind two- and three-dimensional foils used for maneuvering, hovering, or fast-starting.**
3. **The formation of leading-edge vortices in flapping foils, under steady flapping or transient conditions.**
4. **The interaction of foils with oncoming, externally-generated vorticity.**
5. **Multiple foils, or foils operating near a body or wall.**

Index Terms—**Biomimetics, fish swimming, flapping foil propulsion.**

I. OVERVIEW OF LITERATURE

Biomimetic studies and observations from fish and cetaceans have provided a wealth of information on the kinematics, i.e. how these animals employ their flapping tails and several fins to produce propulsive and maneuvering forces (see reviews in [123], [27]). Recent work with live animals has provided important information on the resulting flow structures ([113], [3], [85], [135], [20], [21], [69]).

The fluid mechanics and force mechanics of foils have been investigated with the goal to understand the principles of this different paradigm of propulsion and maneuvering, so as to apply it to enhance existing technology. The tails of some of the fastest swimming animals closely resemble high aspect ratio foils. As a result, flapping foils have been studied extensively using theoretical and numerical techniques ([72], [137], [138], [74], [13], [51], [83], [114], [115], [94], [95]), and experimentally ([109], [17], [68], [6], [98]).

The harmonic motion of the foil causes unsteady shedding of vorticity from the trailing edge and side edges and tips of the foil, while there are conditions when leading–edge vortices form as well. The patterns of large-scale eddies are shown through visualization in [87], [90], [91], [62], [30], [31], [32], [33], [6], [50]. The number of vortices formed per half cycle varies with the amplitude and frequency of the motion and the shape of the waveform ([62], [6]). Triantafyllou et al. [119] perform a stability analysis of the wake to find that there are non-dimensional frequencies for vortex formation, which are optimal for energy minimization. Data from flapping foils and swimming fish and cetaceans show that they have preferred non-dimensional frequencies close to those for optimal efficiency ([120], [26], [50], [68], [101], [86]).

Visualization results from unsteadily moving foils have been reported by a number of investigators. Freymuth [30] studied the combined heave and pitch motions of a NACA 0015 airfoil in a wind tunnel at Reynolds numbers in the range between 5,200 and 12,000. High values of lift coefficient were associated with the formation of a leading edge vortex, also referred to as a dynamic stall vortex, which for specific parametric combinations was subsequently amalgamated with trailing edge vorticity. Reynolds & Carr [99] had provided insight earlier on the basic mechanism governing leading-edge vorticity generation.

Maxworthy [81], Ellington ([23], [25]), Freymuth [32] and Dickinson ([18], [19]) studied the aerodynamics related to the flight of hovering insects and concluded that unsteady flow mechanisms play a very important role. The three principal mechanisms increasing the unsteady lift are [19]: (a) delayed stall; (b) rotational circulation in the form of an unsteady

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Magnus effect; (c) wake capture. Further studies in [16], [125] have put in question the effect of wake capture and have given a different interpretation on the effect of rotation.

McCroskey [77] provides extensive coverage of the effects of unsteady flow mechanisms on foils, including dynamic stall vortex formation. Ellington [23] notes the significant delay in stall caused by unsteady effects, as found earlier, for example, by Maresca et al. [78] for a foil at large incidences in steady flow undergoing axial oscillations. Ohmi et al. ([88], [89]) studied the vortex formation in the flow around a translating and harmonically pitching foil at Reynolds numbers between 1,500 and 10,000, with mean incidence angle of 15o or 30o. At larger incidences they find that the patterns in the vortex wake depend on whether the translational or rotational motion dominates the flow – determined primarily by the reduced frequency. In the case of the flow dominated by the rotational motion, the governing parameter is the product of the reduced frequency and the pitch amplitude, which is the same as the Strouhal number. The interaction of leading edge vortices with trailing edge vortices determines the patterns in the wake.

Anderson et al [6] studied experimentally the propulsive efficiency of a steadily flapping, two-dimensional foil and classified its propulsive performance in terms of the maximum angle of attack, non-dimensional frequency of oscillation, and vortical structures in the wake. Optimal performance was connected with moderately large angles of attack, formation of two vortices per cycle, and the development of mild leading edge vortices.

Freymuth [33] and Hart et al [45] provide flow visualization around rectangular, finite aspect ratio wings, showing complex interconnection among all vortical patterns, including vortices generated at the leading and trailing edges.

These considerations apply to maneuvering as well: Separation drag during fish maneuvering provides forces far exceeding inertia forces; hence it must be avoided by all means. The agility of the pike and trout, reaching accelerations in excess of several g's, is a testament to the fact that fish avoid separation. Measurements on fish maneuverability show that they are more agile than man-made vehicles by about an order of magnitude ([8]).

Finally, cavitation properties of flapping foils are largely unknown. Limited work on foils has shown that the cavitation properties depend on the quality of water as well as on the reduced frequency and amplitude of oscillation ([45], [5]).

A. The Formation Of Leading-Edge Vortices In Flapping Foils, Under Steady Flapping Or Transient Conditions

Leading edge vortices were identified as the source for a number of important effects on flapping foils: Delayed stall, i.e. the delay of large separation effects to large angles of attack, and the rapid generation of significant unsteady lift forces before any vorticity is shed ([81], [23], [32], [43], [18]).

The ingenuous description of lift production through the "Weis-Fogh" mechanism ([133], [72]) had to be revised by the development of leading edge vortices, to account for a discrepancy by a factor of three in lift generation [82]. Hence, leading edge vortices (LEV) can be a very important factor in lift development. Work with insects and small flying animals shows that LEV, in conjunction with potential flow mechanisms, such as the Weis-Fogh mechanism, can be used to generate large lift forces. There is a penalty, though, when large LEV develop, because there are large separation-like pressure gradients which result in large drag forces as well as lift forces. Investigation of the use of the Weis-Fogh mechanism for applications, as suggested by Furber & Ffowcs Williams [35], resulted in relatively low efficiency [121]: below 55% in general and much less in most cases. Flying insects are also reported to have low lift to drag ratio.

II. STEADILY, OR QUASI-STEADILY OPERATING FOILS

Extensive work has been performed in the aeronautics literature on enhancing lift in foils operating under steady or quasi-steady conditions, and reducing drag [64].

Streamlining the foil is a first and obvious step. The uncanny resemblance between NACA sections and fish forms was first noted by von Kármán ("Aerodynamics" 1963). Indeed, the NACA profile NACA63A016 is almost indistinguishable to the profile Sir George Cayley had found for a trout, depicted in his book published in 1810, about a hundred years earlier than NACA profiles were developed.

For three-dimensional foils, an elliptical loading across the span and rounded edges are theoretically predicted to be the optimal form to reduce so-called "induced drag" effects, i.e. the influence of the foil end effects, such as tip vortices, on lift and drag coefficients. Aspect ratio is the principal parameter affecting lift production in a streamlined foil. High aspect ratio wings provide high lift capacity, comparable to that predicted for a two-dimensional foil, with small associated induced-drag coefficient. Rounded edges provide loss of effective span compared to foils with sharp edges; hence the benefit predicted by theory for rounded edges is not very significant. Also, although elliptical distribution of lift gives minimum theoretical lift induced drag, experiment shows rectangular wings to be almost equally effective. Most effective are rectangular moderately-tapered wings.

Hence, concerning plan form and wing tip shape, the aspect ratio is the primary quantity. A tapered rectangular form appears optimal with taper ratios between 0.3 and 0.4, which show little added drag (1-2%) A straight trailing edge appears to be the most effective for lowering induced drag. Delta wings exhibit very good lift to drag ratios as well, despite theoretical predictions to the opposite.

To reduce the effect of tip vortices, end appendages have been proposed, which have an effect similar to end walls—to a certain degree. In practice, it has been found that end plates are useful only for high lift coefficient, above 0.3. Trailing vanes, winglets, and tip sails, are good for improving performance of existing wings, but a to-be-designed wing can always be made as good without them, by proper aspect ratio choice.

Various means for reducing or eliminating stall, and for improving lift production of quasi-steadily operating wings have been proposed, some of them employing some unsteady excitation ([75], [136]). Trapped vortices above the suction side of the wing have been tested, such as the "Kasper wing" ([16], [15], [134], [65]). The stabilization of the vortex on the wing presents a major problem, since spanwise blowing - or suction - may be required to ensure that the vortex is not entrained or that the flow does not separate as vortices of opposite sign are formed, entraining the attached vortex away from the wing.

III. FLAPPING FOILS IN BIRD FLYING VS. FISH SWIMMING

Extensive work on flying and swimming animals has identified some basic mechanisms employed through unsteadily moving foils to produce the forces needed for propulsion and maneuvering of birds and fish. The need for large lift forces in insects has forced them to employ unsteady lift-enhancing mechanisms mentioned in the previous section. Dickinson [19] classifies them as delayed stall, rotational circulation, and wake capture. Delayed stall, the generation of large leading-edge vorticity, possibly stabilized by spanwise flow through the core of the leading edge vortex is well established ([81], [23], [99], [18]). Rotational velocity is also well known to enhance lift if properly timed ([88], [89]). Wake capture means the interaction of the foil with previously shed vortices, especially if energy is recovered from them.

Swimming animals employ some of the same mechanisms with flying animals to produce forces, but the circumstances of swimming differ drastically from those of flying: Whereas the primary difficulty in flying is the continuous production of steady lift to balance the large body weight within a medium with small density, the major difficulty in fish swimming is to minimize drag forces within a medium a thousand times more dense than air - hence, the generation of steady lift to support the weight is of secondary or no importance at all. Fins and foils in water are used for continuous production of thrust or bursts of short-duration forces for maneuvering; birds must continuously support their weight in addition to any other function. A comparison of the pleated wings of an insect ([61]) with the perfectly streamlined fins of most fish and cetaceans points to the same fundamental difference in consideration: the drag penalty for fish is far more important than in birds.

As already stated, there are similar mechanisms at work in fish and birds:

- The formation of leading edge vortices ("delayed stall").
- Influence of shed vorticity through the stable formation of Kármán streets, or interconnected patterns in fast-starting foils. What is termed "wake capture" in Dickinson [19] is a form of shed vortex-foil interaction.
- Effective angle of attack and angular velocity ("rotational circulation").

These mechanisms exist in fish as well ([3], [85], [135]), but not to the pronounced degree exhibited in insects, for example. In Anderson et al [6] a mild leading edge vortex (LEV) is found to benefit efficiency, but a large LEV leads to very low efficiency and high drag.

Measurements of forces and power in flapping foils ([6], [98]) show that for optimal parametric combinations the drag on a flapping foil is very close to the drag on a steadily towed foil at zero angle of attack, resulting in high efficiency. In contrast, insects which must produce very high lift forces at low or zero forward speed, generate very high drag as well [25].

The physical mechanisms of force production in unsteadily flapping foils have been elucidated for flying animals, because of the large motions required to produce large lift. The particular needs of operation underwater, i.e. low drag and high efficiency at high Reynolds number, result in important differences from foils used for flying.

IV. A REVIEW OF BASIC MECHANISMS

A. *Steadily Oscillating Two-Dimensional Foils*

The idea of forming spatially periodic patterns of vortices behind flapping foils has come out "naturally" out of the early work by Lighthill [72] and Wu [137]. More recent work has studied the effect that different patterns of vortices have on the forces and efficiency of foils. For two dimensional foils, and high aspect ratio foils away from the ends, a planar cut in the wake shows that two vortices per cycle are the optimal pattern, resulting in the formation of a "reverse Kármán street"; more than two vortices may form ([62], [68]), resulting in degradation of thrust generation and propulsive performance ([62], [6]).

Pitching-only foils [62], heaving-only foils [50], as well as heaving and pitching foils ([109], [6]), exhibit reverse Kármán streets. For large Strouhal number, heaving only foils exhibit an instability whereby the Kármán street is developed at an angle with respect to the oncoming velocity, resulting in steady lift. There is no preferred direction, i.e. the street may be inclined with a positive or negative angle, depending on the initial conditions, while small disturbances can cause random switching in direction.

As found in [42], delta wings exhibit no dependence on the reduced frequency until large angles of attack are used; because the vortices forming from the sides remain attached and are convected downstream through a helical motion. Hence there is no characteristic time scale. In contrast, high aspect ratio foils which form leading edge and trailing edge vortices depend strongly on reduced frequency.

Figure 1 [6] summarizes the observational data on the flow around two-dimensional flapping foils as function of the angle of attack and the Strouhal number. The Strouhal number, is defined as $St = fA/U$, where f denotes the frequency of foil oscillation, A denotes the characteristic width of the created jet flow, and U the speed of the foil.

We distinguish several regions: In regions A and B ($St < 0.2$) the wake does not roll up into discrete vortices; in region B a very weak leading edge vortex appears for $a_{max}>30°$, but the wake retains its wavy form. For angles of attack larger than about 50° a "piston" mode appears where leading and trailing edge vortices form and roll up in the wake to form four vortices per cycle. In region E, for angles of attack smaller than 5º, the wake does not form distinct patterns. Region C, contained in the limits: $7° < a_{max} < 50°$ and $0.2 < St < 0.5$, is characterized by the formation of a clear reverse Kármán street. A leading edge vortex forms for angles of attack larger than about 10°, increasing in strength with increasing angle of attack, which is amalgamated with trailing edge vortices to form two vortices per cycle. Region D ($St>0.5$) is characterized by the formation of leading edge vortices, which interact with trailing edge vorticity to form four vortices per cycle. Data for lower h_o/c show nearly identical trends as far as the wake form is concerned; the formation of a leading edge vortex depends on h_o/c, however.

The presence of a leading edge vortex is strongly influenced by the angle of attack. In region C, for St between 0.2 and 0.5, strong thrust develops from a reverse Kármán street, accompanied by up to a moderately strong leading edge vortex. Region C contains the region of optimal efficiency found in the force experiments. In region D, for St larger than 0.5, strong thrust develops accompanied by the formation of two vortices per half–cycle, which have opposite circulation and, in general, different strength. Regions A and B are characterized by low or negative thrust, and a wavy wake with no distinct vortex formation; the leading edge vortex is very weak. In region E, for very small angles of attack, very small or negative thrust develops.

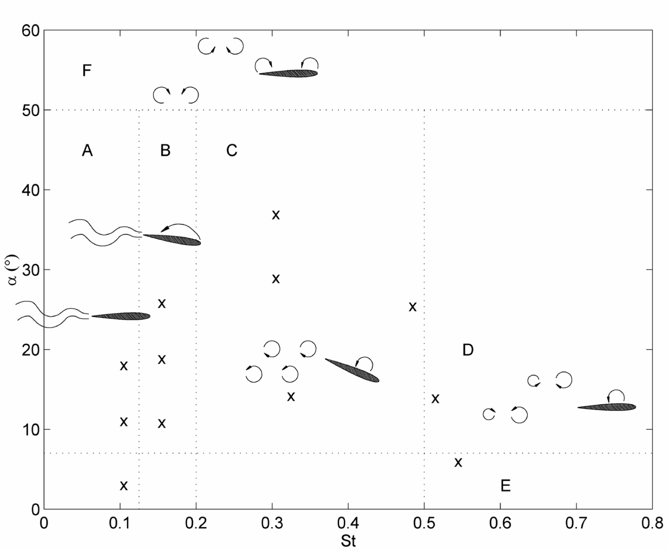

Figure 1: Wake patterns as function of the Strouhal number and angle of attack for ho/c=1. Points mark the location of experiments reported in Anderson et al (1998).

Foils oscillating around a steady angle of attack produce asymmetric wakes, sine they generate a steady lift force ([32], [33]). The wake may be inclined with respect to the oncoming flow, and/or contain larger eddies on one side of the wake, and/or a larger number of vortices on one side of the wake versus the other side. In a hovering mode, i.e. at zero oncoming speed, this allows to vector the force produced [33].

In a study on the efficiency of flapping foils [6], the LEV slightly augmented propulsive efficiency when its circulation is mild, but caused the performance to deteriorate when it grew in strength. LEV can merge with trailing edge vortices to produce a reverse Kármán street. Figure 2 shows a mild leading edge vortex forming on a flapping foil; behind it a reverse Kármán street forms (vortices at the top and center and bottom left). Figure 3 shows a strong leading edge vortex, which has been shed and has reached the trailing edge of a flapping foil. Again, a reverse Kármán street forms back in the wake, consisting primarily of leading edge vorticity.

1) Kutta Condition: In inviscid hydrodynamic theory, the Kutta condition, i.e. the imposition of the following condition: the velocity leaves tangentially from both sides of the foil at the (presumed sharp) trailing edge, with continuous pressure across the edge. This is fundamental to deriving the forces and flow patterns around a steadily or unsteadily moving foil and although the Kutta condition is an artifact of inviscid theory, it adds to our physical understanding; hence it is interesting to consider whether it is valid in an unsteadily moving foil as well.

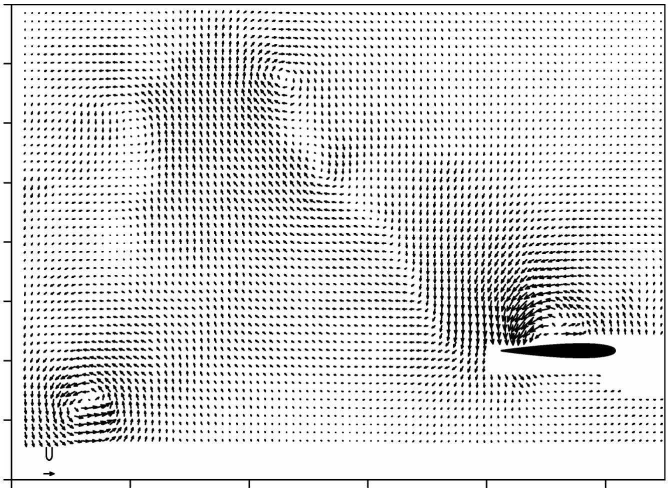

Figure 2: DPIV velocity data for the foil at its minimum heave position, and St=0.45, A/c=1, q=45o, amax=13.3o, y=90o.

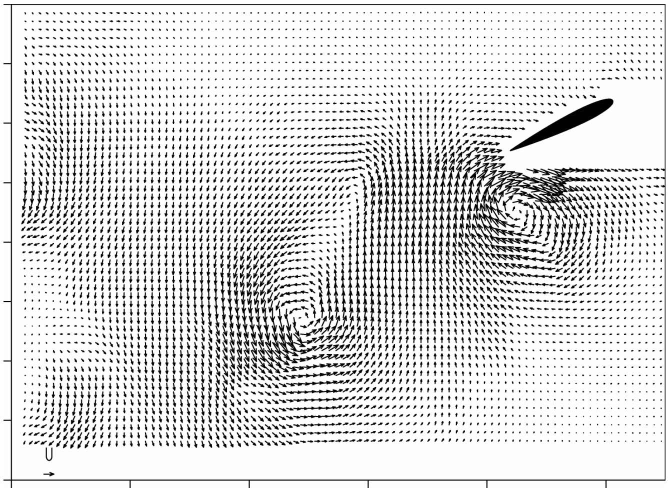

Figure 3: DPIV velocity data for the foil at its maximum heave position, and St=0.30, A/c=1, q=30º, a_{max}=52.7º, y=30o.

Evidence of apparent failure of the Kutta condition at large frequencies led to a number of investigations. Finally, it appears that the Kutta condition is valid if one takes into account possible vortices forming close to the trailing edge ([87], [108], [93]).

B. Steadily Oscillating Three-Dimensional Foils

In three-dimensional foils, the vortical patterns must connect with each other and with the foil producing them. The idea of a chain of alternately inclined—with respect to the direction of motion – interconnected vorticity rings, as sketched by Lighthill [72] provides a consistent qualitative picture for the flow structure behind oscillating foils. Recent work ([20], [21], [69]) shows the formation of ring-like vortical structures by fish fins.

Detailed flow visualization in flapping foils provides a more complex picture: The vortical patterns close partially on themselves to form apparent ring loops, but the vorticity of each loop connects all the way back to the foil ([31], [33], [45]). This is similar to the way Kármán vortices interconnect with themselves and to the body, in the wake of a finite length bluff cylinder, or – in a more simplistic description – to the way helical vortices in the propeller go all the way back to the propeller blade. The only difference here is that the connecting vortices to the foil are entangled in a "spaghetti"-like structure, resembling the hub vortex of the propeller but with the difference that the constituent vortices do not have the same rotational sign. This picture has a significant effect on induced drag and on cavitation. The overall picture in three-dimensional wings is a "curious mixture of two-dimensional and three-dimensional vortex developments..." (Freymuth, 1991).

The performance of three-dimensional foils depends on the reduced frequency (or, equivalently, the Strouhal number), the foil shape and aspect ratio, and the angle of attack. The effect of the aspect ratio is reduced as the reduced frequency increases, because the tip vortices are of alternating sign, hence the induced velocities are significantly reduced. This observation, first made by Karpouzian et al [51], was also reported in the numerical study of Cheng et al [14]. Recent detailed data on three dimensional foils [80] shows little degradation of performance for moderate aspect ratio foils, compared with the results for two dimensional foils. This has also been found in the aerodynamic characteristics of flying animals [19].

Scherer [109] reports efficiency in rectangular, moderate aspect ratio wings of up to 70%; his Strouhal numbers were rather low, however, so he never reached the regions where maximal efficiency is anticipated. Lai et al [67] report efficiencies up to about 75% (with scatter) for a flapping rectangular NACA 16-012 foil with aspect ratio 4. DeLaurier & Harris [17] report efficiencies in the range of 18 to 50% for a rectangular NACA 0012 flapping foil with aspect ratio 4, oscillating with heave amplitude equal to 0.625 chords at Reynolds number 30,000.

The presence of a leading edge vortex in three-dimensional foils depends strongly on the maximum angle of attack, and hence the specific load on the foil. The structure and connection of leading edge vorticity is a difficult subject, because flow visualization pictures are not typically clear. Maxworthy [82] had proposed that in three-dimensional wings leading edge vortices are helical vortices which connect to the tip vortices. Numerical simulations in the wing of a hovering insect ([95], [73]) show a similar structure. This provides for a vorticity shedding mechanism different than in two-dimensional foils, since a helical vortex need not separate to convect downstream. Freymuth [33] shows pictures for low aspect ratio foils under high angle of attack, where both leading and trailing edge vorticity forms. The trailing edge vortices are connected back to the foil edges with alternating sign tip vortices, which appear at some point to cancel each other. This leads to the formation of vortex ring-like structures. The leading edge vortices also form rings but the flow is much more confused. Hence, it is possible to both have a direct connection between the leading edge vortex and the tip vortices, and have leading edge vortex shedding.

Leading edge vortices are an intricate part of flapping foil vorticity above a threshold angle of attack and Strouhal number. In a three dimensional foil these leading edge vortices are interconnected at the ends with bound as well as shed vorticity.

A study of the qualitative and quantitative effect of the leading vortices as their strength increases from the mild values associated with enhance efficiency by Anderson et al [6] to the very intense values found in insect flight [25] has not been performed yet. Such a study will provide a bridge in out understanding between the properties of fins for swimming to those of fins for flight.

1) Three-Dimensional Foils In Combinations Of Feathering, Rowing And Flapping Motion: In a series of papers Kato ([52], [53], [54]) has considered the forces generated by a foil with aspect ratio of order 1 – the aspect ratio found typically in the pectoral fins of fishes [126]. The fins performed three types of motion:

- rowing, i.e. forward-backward motion;
- feathering, i.e. a twisting (or pitching) motion about the axis of the fin;
- flapping motion, i.e. rolling motion about the root attachment of the fin transversely to the flow, when a steady stream exists.

The basic conclusion is that the propulsive efficiency of feathering or flapping foils (lift-based) is larger than the efficiency of drag-based rowing foils, in agreement with Walker & Westneat [128] who show a maximum efficiency of 10% for drag-based, contrasted with about 60% maximum efficiency for lift-based propulsion. Rowing is better-suited for still water force generation, however, providing better maneuverability, since it produces substantial thrust but small transverse forces. Also, it is found that a non-sinusoidal feathering motion combined with a sinusoidal rowing motion produces thrust accompanied with small transverse forces. Maximum efficiencies of the order of 45% are reported for the lift-based mode of propulsion Kato ([55], [56]).

C. Multiple Foils and Foils interacting with Bodies

When two or more foils operate side by side, or foils operate near a wall or are attached to a vehicle, there are important interaction effects taking place. For example, two foils side by side may have strong vortex to vortex interaction effects resulting in a drag wake and serious deterioration of performance. Likewise, interaction with bodies can have similar effects.

Bandyopadhyay et al [10] study a streamlined vehicle equipped with two flapping foils in close proximity. Force and efficiency measurements as well as flow visualization show strong interaction effects that require more parameters than the ones used for single foils.

Flow visualization in two side by side foils shows, similarly, that when foils oscillate very close to each other, a strong drag-wake-like flow develops between the foils causing efficiency deterioration. Experiments with two foils flapping in anti-phase, to emulate the Weis-Fogh mechanism [121], show that such strong interaction can produce sufficient thrust to propel a ship.

Dual foils have also been tested for efficiency. One of the issues in dual foils is the strong interaction between the wakes of the foils, which can take many forms:
(a) the wakes can collapse into a single wake; (b) the wakes interact strongly forming two jets divided by a backflow region, which can deteriorate performance seriously; or (c) the foils can be well separated, providing good thrust performance. When foils flap against a body, or against a second foil, the conditions of the Weis-Fogh mechanism apply. Large forces are produced but these include large drag forces as well, while the resulting vortical patterns usually are different from single foils. In Tsutahara & Kimura [121] the Weihs Fogh mechanism is used to produce thrust for ship propulsion. Two rectangular plates with aspect ratio 1.8 were used up to Reynolds number 300,000. The efficiency was up to 58% for angular amplitude of 15 deg., lower for other conditions. Bandyopadhyay et al ([9], [10]) employed two foils flapping against a middle flat plate. They report efficiencies up to 30%, while the vortical patterns form a rapidly expanding wake.

D. Foils Interacting With Oncoming Unsteady Flows

Foils will invariably operate in environments that contain unsteady flow such as waves near the surface of the ocean; and large vortical structures and/or turbulence when operating in the wake of a propelled body, or in the wake of another foil or propeller. Several foils interacting with each other, a foil in the wake of sharply maneuvering object, foils operating with a turbulent ocean are only a few examples.

Hence, the investigation of interaction between two-dimensional vortices and two dimensional foils must be extended to interaction of incoming vortices with finite aspect ratio foils. Parametric ranges for which 2D-foil efficiency increases due to interference with oncoming vorticity have been identified by Gopalkrishnan et al [40], Streitlien et al [115] and Beal et al [11].

E. Maneuvering Foils

Flapping foils which are used to generate forces for maneuvering must either provide a steady lift force, often in addition to thrust; or provide a short-lived, high-magnitude force. There is close connection between flapping foils used for propulsion and those used for maneuvering since both depends on unsteady flow mechanisms to develop forces. The details differ, however, and hence the physical mechanisms and properties have differences as well.

Experiments to study the development of transient forces are relatively few. They contain cases of foils performing a transient motion ([2], [98], [80]); foils performing a flapping motion with a superimposed bias angle to develop steady lift forces ([88], [89], [98]); and combination of rowing, plunging and feathering motions with bias angles to develop non-sinusoidally varying lift forces that can be used for positioning and maneuvering ([52], [54], [55], [56], [79]).

Hertel [46] and Ahlborn et al [2] showed that a flapping foil develops a pair or pairs of interconnected vortices (which appear like rings in a three-dimensional view) when starting from a position of rest and performing a complete cycle of heave or pitch motion. Drucker & Lauder ([20], [21]) show the formation of sequences of inclined, interconnected ring-like structures in the wake of flapping pectoral fins of live fish.

As reported in Ohmi et al [89], the bias angle in a pitching foil plays a significant role in determining the flow patterns up to a threshold Strouhal number – in the nomenclature of the authors, instead of Strouhal number, they use the product of reduced frequency and angle of oscillation.

In [98], [80] a bias angle is used to produce steady lift in unsteadily flapping foils. Significant steady and unsteady lift, which is much higher, up to an order of magnitude, than under steady conditions, can be produced. The moderate aspect ratio, three-dimensional foil in Martin et al [80] produced steady and unsteady lift forces comparable to those experienced by the two-dimensional foil employed by Read et al [98]. This demonstrates once more that end-effects are less important in unsteady foils than steady foil, in accordance with the findings in [51], [14], [25].

F. The Interaction Of Foils With Oncoming, Externally-Generated Vorticity

The study of the interaction between the wake of an upstream body and a downstream foil, the study of the interaction between foils in cascade, and foils in turbulent flow, require an understanding on how externally generated vorticity interacts with foil generated vorticity. Hence, multiple foils interacting with each other; and foils in the wake of upstream bodies, subject to organized shed vorticity or wake turbulence, require an understanding of how such vortical interactions affect the performance of the foils. This information can be valuable, since it can be used to preserve performance through sensing and closed loop control; and to study under what conditions – and how – such interactions can be used to actually improve propulsive performance [40].

Sparenberg & Wiersma [112], Koochesfahani & Dimotakis [63], Gopalkrishnan et al [40], and Streitlien et al [115], have performed theoretical and experimental studies on the interaction of foils with upstream vorticity. Gopalkrishnan et al [40] identified three modes of interaction:

- Upstream vortices are repositioned and then interact destructively with foil-generated vortices of the opposite sign to create a field of weak vortices (destructive mode), resulting in substantial increase of efficiency.
- Upstream vortices are repositioned and then join foil-generated vortices of the same sign to create a field of vigorous vortices (constructive mode), resulting in increase of thrust at the expense of reduced efficiency.
- Upstream vortices are repositioned and then pair with foil-generated vortices of the opposite sign to create a field of vortex pairs, appearing in visualization as “mushroom-structures”, resulting in a wide wake (pairing mode), resulting in a great variety of responses depending on the timing of vortex pairing.

Further work by Anderson [3] showed that there is one more dimension to the problem: Leading edge vorticity can interact early with oncoming vorticity resulting in patterns that resemble qualitatively the three major patterns of Gopalkrishnan et al [40] but differ in several aspects of the flow especially close to the foil, hence affecting performance.

G. The Influence Of Cavitation On Foil Performance

While cavitation in steadily moving foils is understood [5], this can not be said for unsteady foils, where vortices form close to the foil, migrate in its wake, and interact with each other. The interaction among the tip vortices is of the destructive type, since the angle of attack is oscillatory – which explains why reduced frequency has often a beneficial effect, i.e. reducing cavitation.

Cavitation in unsteadily moving foils is known to be influenced by the reduced frequency of oscillation, but the information is very sparse and restricted to mostly visual observation ([5], [45]). The vortical structure around the foil affects the cavitation properties significantly, so such an investigation must follow immediately after the investigation on the structure of the flow around and behind foils. First, the optimal range of foil operation must be investigated, i.e. with moderate angles of attack and Strouhal number; followed by larger angles of attack.

H. *Effect of Geometry And Flexing Stiffness of Foils*

Fish fins present great variability in shape, aspect ratio and structure, depending on the application they are intended for. Pectoral fins, for example, may have the shape of moderate- or low-aspect ratio foils for some fish; while for others, such as whales, large aspect ratio foils are used. Also, the flexibility of the foils ranges greatly. No systematic experimental study of flexing foils has been reported. Foils can flex along their chord and/or along their span. Fish certainly employ passive flexibility and possibly actively controlled flexibility.

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