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On the Use of Vortex Flows for the Propulsion of Micro-Air and Sea Vehicles

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Abstract

Recent interest in flapping-wing propulsion, in particular for hovering or low-speed flight of micro air vehicles, has led to a renewed interest in the measurement and prediction of unsteady, vortex-dominated flows. The proposed vehicles operate at Reynolds numbers below 20,000, and operate with mildly to fully separated flow throughout the flapping cycle. This paper provides a brief history on the topic, and summarizes research efforts at the Naval Postgraduate School over the last decade, demonstrating the current numerical and experimental capabilities, and indicating areas where further work is required. Specifically, several wind and water tunnel experiments are described where the vortex structures generated by single flapping foils and by two foils arranged in a biplane configuration were visualized and thrust was measured as a function of flapping amplitude and frequency. Additional experiments are reported which show the potential of flapping foils to energize flat-plate boundary layers and to suppress or reduce regions of flow separation. Two- and three-dimensional panel code code and two-dimensional Navier-Stokes computations are also described to analyze these flapping-foil experiments.

Introduction

The use of flapping-wing propulsion dates back much further than the forms of propulsion considered to be *conventional* in today's mechanical world. Indeed, nature has predominantly selected flapping-wing propulsion as the optimal approach, however, whether this choice is one of organic constraints or one of optimal performance is an unsettled matter. Nevertheless, the fact that birds, insects and many sea creatures utilize flapping-wing propulsion with great success, at the very least, merits a thorough scientific investigation. Of course, this is primarily an academic argument to pursue the topic, one which, until recently, has chiefly relegated flapping-wing research to something of a hobby-like status. The necessary financial support for more dedicated research has recently come about as a result of DARPA's interest in the development of Micro Air Vehicles (MAVs).

The scientific history of flapping-wing propulsion is rather lengthy, dating back nearly a century. In 1909 and 1912, respectively, Knoller and Betz were the first ones to explain the bird's ability to generate a forward thrust by means of wing flapping. In 1922, Katzmayr provided the first experimental verification of the Knoller-Betz effect in wind tunnel tests at the Technical University of Vienna. The first theoretical investigations of the aerodynamics of flapping wings are due to Birnbaum (1924), von Kármán and Burgers (1935) and Garrick (1936). These studies, based on flat-plate theory, showed that the propulsive efficiency of a flapping airfoil decreased from 100 percent to 50 percent as the reduced flapping frequency increased from zero to infinity.

In 1942, Schmidt recognized that the Knoller-Betz or Katzmayr effect applied to both a flapping airfoil in a uniform flow and a stationary airfoil in an oscillating flow. He demonstrated experimentally that a stationary airfoil located in the wake of a flapping airfoil increased the propulsive efficiency to almost 100 percent throughout the frequency range, because the stationary airfoil converted the vortical energy expended by the flapping airfoil into additional thrust. He also found that the mechanical limitations inherent in pure flapping motions could be overcome by an arrangement he called the wave propeller, where the pure flapping motion was replaced by a circular airfoil motion while maintaining the airfoil's incidence angle. In addition, he found that a wave propeller mounted downstream of a large airfoil at high incidence could delay the onset of airfoil stall.

Bosch (1978) presented results for oscillatory interference effects using the oscillatory kernel

function method. In support of Schmidt's measurements, he showed that a harmonically flapping airfoil upstream of a stationary airfoil increased the propulsive efficiency to almost 100 percent. However, Bosch's analysis was limited to flat-plate airfoils oscillating about a zero incidence mean position.

Schmidt (1965) demonstrated the practical utility of his wave propeller on small catamaran boats, and cited as a major advantage its ability to operate in shallow waters. In the sixties, the U. S. Army recognized that propulsion of a boat in weedy, shallow waters by means of a rotating propeller was very difficult, as weeds tended to block the inlet to the system and wind around the rotating shaft of the impellers. To alleviate this problem, the U. S. Army Engineering Research and Development Laboratories supported an experimental and theoretical investigation of large amplitude oscillating foil propulsion systems at Hydronautics Inc (Scherer, 1968). Thrust and lift forces generated by a NACA 63A015 airfoil section due to pitch and plunge oscillations were measured in a high-speed water channel, and it was concluded that it was feasible to propel a 15-knot, shallow-draft boat of 2000 pound payload by means of a flapping foil propulsion system.

Vortex Structures Generated by Single Flapping Foils

The flow over a stationary airfoil at low Reynolds numbers produces the Kármán vortex street shown in Fig. 1. As indicated, the measured time-averaged velocity distribution in the wake shows a distinct velocity deficit, indicative of drag. However, the periodically plunging foil shown in Fig. 2 produces a reverse Kármán street. The upper row of vortices are now counter-clockwise and the lower ones are clockwise. As indicated, the time-averaged velocity distribution is a jet-like distribution, indicative of thrust.
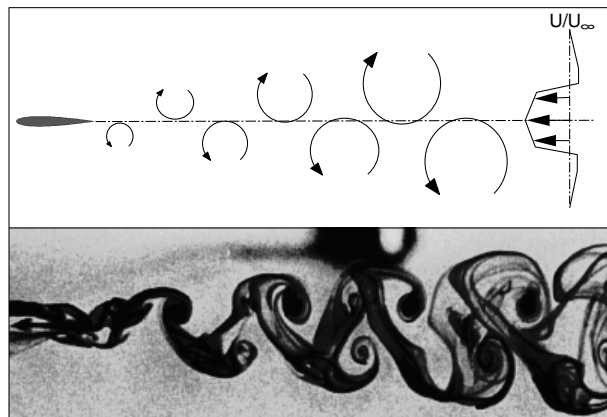

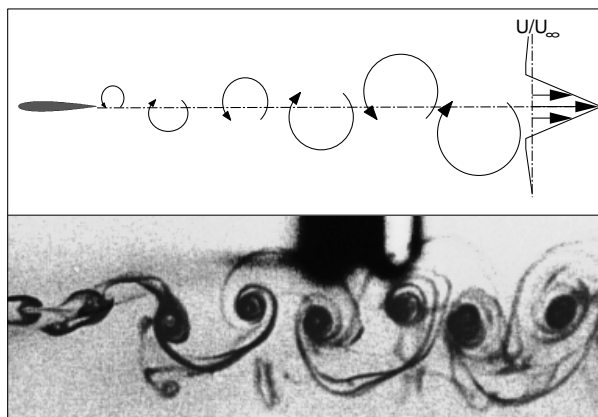*Fig. 1:* Drag indicative vortex street.

Fig. 2: Thrust indicative vortex street.

Koochesfahani (1989) visualized the vortices shed from a NACA 0012 airfoil pitching sinusoidally about its quarter chord point. He also obtained LDV measurements of the time-averaged velocity profiles downstream of the trailing edge. He found that the vortex pattern indeed switches from drag-indicative Kármán vortex streets to thrust-indicative streets. A direct assessment of the drag/thrust from the measured wake deficit or surplus, however, is quite difficult and we refer to Fig. 13 and our discussion of this problem in Jones *et al.* (1998).

Jones *et al.* (1998) visualized the shed vortices behind sinusoidally plunging airfoils in a water tunnel, and measured time-averaged velocity profiles in the wake using LDV. Based on visual observations of the vortex locations, they showed that the formation of drag or thrust-indicative wakes could be predicted based on the product of the reduced frequency and the non-dimensional plunge amplitude, which we refer to as the plunge velocity (mathematically, the Strouhal number times π). The Reynolds numbers for this study were in the range 500 to 50,000 and, in this range, it was found that lines of constant plunge velocity of 0.4, 0.7 and 1.0, roughly classified the experimental results into drag, neutral, thrust, and a lift/thrust-indicative wakes, respectively. The lift/thrust-indicative or deflected wakes were found for highly energetic motions (high frequency and/or amplitude) and, surprizingly, were duplicated quite well numerically by an unsteady panel code, as shown in Fig. 3.

The panel code, described in Platzer *et al.* (1993), utilizes a deforming wake model which accurately predicts vortex roll-up.

LDV measurements of time-averaged velocity profiles downstream of the airfoils were compared to the panel code, agreed well for most thrust-indicative wakes, as shown in Figs. 14 and 15 of Jones *et al.* (1998). At a plunge velocity of 2.3, while the measured and computed profiles were similar in nature, the LDV-measured velocity profile indicated a much greater wake deflection, suggesting the influence of leading edge separation, although at the time it was not measured or visualized conclusively. Further work is needed to better understand the interaction between leading and trailing-edge vortices.

Lai and Platzer (1999) performed similar experiments for harmonically plunging NACA 0012 foils, using dye flow visualization and LDV for the measurement of the time-averaged velocity profiles. The tests were conducted in water at freestream speeds ranging from 0.05 to 0.21 m/sec, which resulted in Reynolds numbers from 500 to 20100. They also classified wake structures based on the plunge velocity, and found that the lines of constant plunge velocity of 0.3 and 1 separated the wakes into drag, thrust and lift/thrust-indicative (shown in their Fig. 7), in agreement with Jones *et al.* (1998). They also found that LDV measurments crossed from a velocity defecit to a velocity surplus at roughly a plunge velocity of 0.25.

Fig. 3: Deflected wake comparison ($kh = 1.5$).

As previously noted in connection with Koochesfahani's measurements, it is difficult to convert the measured velocity defect or surplus into drag or thrust. However, it was clear that drag was generated at speed ratios less than 0.25 at the tested Reynolds numbers. It is therefore interesting to compare the measurements with Navier-Stokes computed force values. In Fig. 6, from Tuncer and Platzer (1996), Navier-Stokes computed thrust and propulsive efficiency values are shown for the sinusoidally plunging NACA 0012 airfoil at a chord-Reynolds number of 3 million, as well as a comparison with oscillatory thin-airfoil theory. It is seen that thrust is predicted for all values of amplitude and frequency down to vanishingly small values. At this Reynolds number, the Navier-Stokes solutions agree well with potential-flow theory, but differ with the much lower Reynolds number experimental findings. As one would expect, the thrust increases with increasing values of plunge amplitude and frequency. As already mentioned, linear theory predicts very high values of propulsive efficiency at low frequencies, decreasing to 50 percent with increasing frequency. It is apparent from the measurements and from the Navier-Stokes computations that the viscous effects nullify this optimistic prediction for the low frequency range, a fact that will be even more pronounced at low Reynolds numbers.

Since thrust increases with increasing amplitude and frequency, the question arises whether it is more efficient to achieve a required thrust value by increasing amplitude and minimizing frequency or vice versa. This question can be answered to some extent by looking again at Fig. 6 of Tuncer and Platzer (1996). A given thrust coefficient, say 0.1, can be obtained with an amplitude of 0.3 and a reduced frequency of 0.5. If the amplitude is increased to 0.4 the reduced frequency is lowered to approximately 0.4 and the propulsive efficiency is generally increased (unless too small values of amplitude and frequency are chosen). This conclusion is further substantiated by Navier-Stokes computations of Tuncer *et al.* (1998) who investigated the dynamic stall characteristics of a
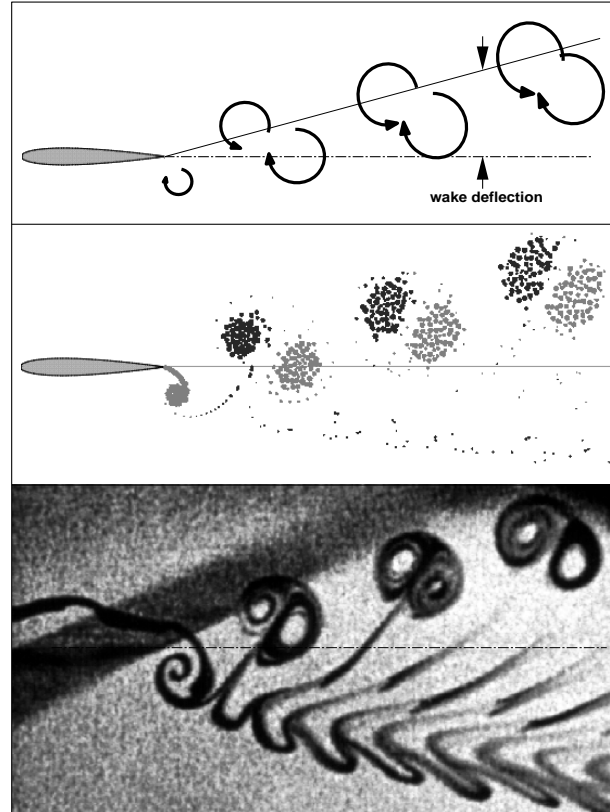
sinusoidally plunging NACA 0012 airfoil at a Reynolds number of 1 million. As seen from their Fig. 3, dynamic stall is predicted as soon as the non-dimensional plunge velocity hk exceeds a value of approximately 0.35. Hence one can choose either a large amplitude and a small frequency or vice versa. However, if one wants to optimize the propulsive efficiency, it is advantageous to operate in the large amplitude/low frequency range, as shown in Figs. 11a and 11b of Jones and Platzer (1997) and Fig. 4 of Tuncer et $al.$ (1998).

Birds generally use a combination of pitching and plunging motion rather than a single degree of freedom pitch or plunge motion as discussed above. This expands the parameter space considerably. In addition to the pitch and plunge amplitudes one now has to consider the phase angle between the pitch and plunge motions. It is important to realize that the key parameter for determining whether an airfoil generates thrust or extracts power from a flow is the effective angle of attack, as illustrated in Fig. 4.

Cases (a) and (b) represent the pure plunge and pitch modes. Case (c) is the neutral case (pure feathering) between thrust generation and power extraction. A negative effective angle of attack (relative to the flight path) leads to thrust generation, case (d), a positive angle to power extraction, case (e). Utilizing the panel code, thrust, power, and propulsive efficiency can be studied as a function of phasing between pitch and plunge. This is shown in Figs. 5 and 6 (taken from Jones and Platzer, 1997). It is seen that for the parameter combination chosen in Fig. 5 thrust is generated for any phase angle between pitch and plunge, but the optimum efficiency occurs at around 90 degrees. Unfortunately, this corresponds to a minimum in the thrust coefficient. On the other hand, for the parameter combination of Fig. 6, power is extracted for phase angles near 90 degrees at both the highest efficiency and maximum power extraction. These findings are consistent with earlier results obtained by Lan (1979) for a rectangular wing of aspect ratio 8 using an unsteady quasi-vortex-lattice method.
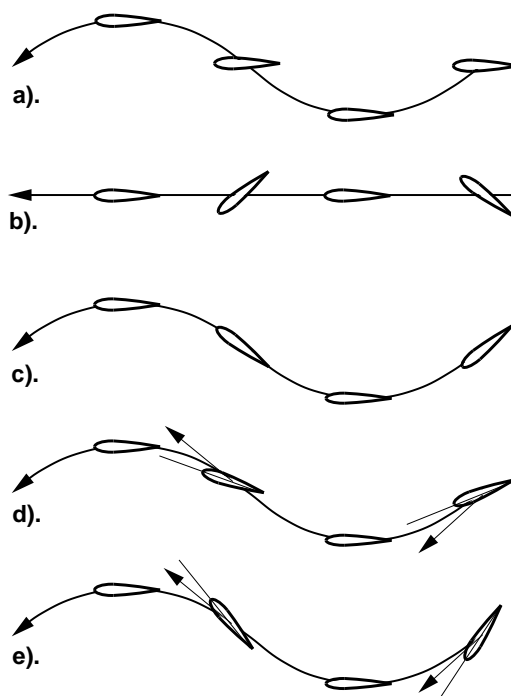

Fig. 4: Effective versus geometric incidence.

The predictive power of any inviscid flow theory must be evaluated by comparison with direct measurements of the thrust generated by flapping wings. Anderson et $al.$ (1998) presented thrust and power measurements for a NACA 0012 airfoil executing combined plunge and pitch motions at a Reynolds number of 40,000 and found good agreement with inviscid flow models over a certain parametric range. However, they also identified other test cases which revealed large discrepancies between inviscid theory and experiment. Consistent with the findings of Lai and Platzer (1999) mentioned earlier poor agreement was obtained with low frequency tests (where viscous effects are expected to be quite strong). Another phenomenon which cannot be easily modeled with inviscid flow theories is the shedding of leading edge vortices. In a series of flow visualization experiments Anderson et $al.$ (1998) demonstrated the formation of leading edge vortices and, most significantly, showed that high thrust values can be achieved with high propulsive efficiency if the shedding of the leading edge vortex is properly timed. This seemed to occur for phase angles of about 75 degrees between the pitch and plunge motion.
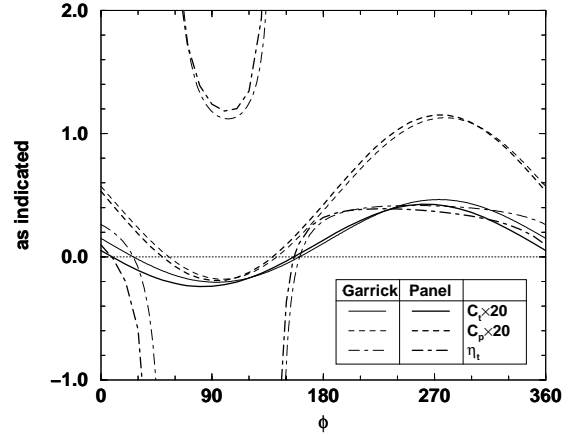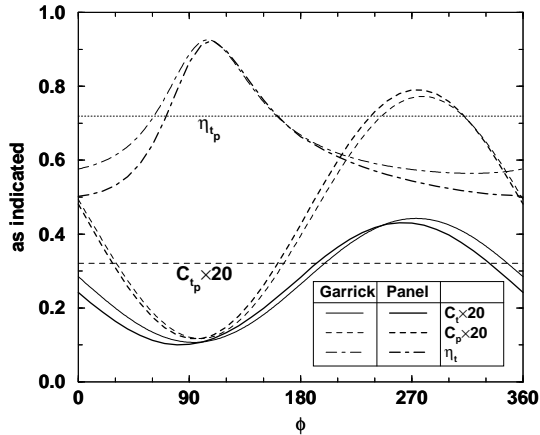
Fig. 5: Results for $k = 0.5$, $h = 0.2$ and $\Delta\alpha = 4°$.   *Fig. 6:* Results for $k = 0.5$, $h = 0.2$ and $\Delta\alpha = 8°$.

These results show the importance of determining the dynamic stall boundaries of flapping airfoils, both experimentally and computationally. Tuncer *et al.* (1998) and Tuncer and Platzer (2000) therefore attempted to determine the dynamic stall boundary of the NACA 0012 airfoil at high Reynolds numbers using a Navier-Stokes analysis. In Fig. 1 of Tuncer *et al.* (1998) it is shown that a drastic loss of thrust is predicted for the sinusoidally plunging airfoil as soon as the dynamic stall limit is reached. Also, it is seen that the comparison with the inviscid panel code prediction is quite good below the stall limit.

Further Navier-Stokes calculations were made by Tuncer *et al.* (1998) and by Isogai *et al.* (1999) to determine the dynamic stall boundaries of NACA 0012 airfoils in combined pitch and plunge motion. Their calculations are generally in good agreement and show that the highest efficiency is obtained when the pitch oscillation leads the plunge motion by 90 degrees and no appreciable flow separation occurs. Using a finite element incompressible Navier-Stokes solver, Ramamurti and Sandberg (2001) extended these calculations to the experiments of Anderson *et al.* (1998) involving the shedding of strong leading-edge vortices at Reynolds numbers of 1100. Their computations confirmed Anderson's observations that the phase angle between the pitch and plunge oscillation is the critical parameter in maximizing thrust or propulsive efficiency. Further computations and experiments are clearly needed to draw more definitive conclusions.

The special case of airfoil oscillation in a still medium provides additional interesting insights into the flow physics of flapping airfoils and confronts the computational aerodynamicist with a considerable challenge. Lai and Platzer (1998) studied the flow generated by a sinusoidally plunging NACA 0012 airfoil in still water using dye visualization and LDV techniques. They found that vortices are shed from the *trailing edge* and a jet is produced with a time-averaged jet velocity which is greater than the peak plunge velocity for several chord lengths downstream of the trailing edge. Consistent with the earlier findings the jet axis is deflected relative to the chord line because the non-dimensional plunge velocity now tends toward infinitely large values. Airfoils having a sharp trailing edge and a rounded leading edge therefore generate static thrust. However, the precise flow details around the leading edge could not be ascertained in these tests. The effective angle of attack induced by the plunge oscillation is certainly very large and it is likely that dynamic stall vortices are shed from the leading edge. Further experimental and computational studies are required to identify the precise flow features.

Vortex Interference Effects

It is apparent from the above review of the flow physics of single flapping foils that our understanding and prediction of flapping foil aero/hydrodynamics is largely limited to cases where no or little flow separation occurs. Yet, it is also clear that dynamic stall is likely to occur in many practical applications. Unfortunately, it is still unclear whether the dynamic stall phenomenon limits the use of flapping foil propellers or whether it is possible to take advantage of it for the generation of significant thrust values with high propulsive efficiency.

As already mentioned, Schmidt (1965) sought to develop an efficient flapping foil propeller by exploiting the interference effect between a flapping fore-wing and a non-flapping hind-wing. The stationary hind-wing is exposed to an oscillatory flow and therefore can exploit the Katzmayr effect, i.e., convert the vortical energy generated by the flapping fore-wing into additional thrust. Bosch (1978) presented the first computational analysis of this tandem foil arrangement using oscillatory thin-airfoil theory. Platzer *et al.* (1993) generalized the previously mentioned unsteady panel code to the computation of incompressible flow past two oscillating airfoils whereby the position of the two airfoils relative to each other can be quite arbitrary. Hence it is possible to study the interference effects between two oscillating airfoils. Two arrangements are of greatest interest, namely the tandem and the biplane arrangement, shown as Fig. 7b and 7c, respectively.

The latter arrangement is equivalent to a single airfoil oscillating in ground effect provided the oscillation of the two airfoils in the biplane arrangement occurs in counter-phase. Jones and Platzer (1999) performed a more detailed computational and experimental investigation of both arrangements. To this end the model shown in Fig. 8 was built and tested which allowed the flapping of the two fore-wings in either a pure plunge mode or a combined pitch/plunge mode with the optional mounting of two stationary hind-wings as shown in Fig. 7d. For a detailed description of the laser technique used to measure the thrust we refer to this paper. The panel code analysis reveals that the biplane arrangement (or flight close to a ground plane) has a quite favorable thrust enhancement effect.

This prediction could be confirmed with the thrust measurements shown in Fig. 18 of Jones and Platzer (1999). On the other hand, the Schmidt effect could not be confirmed in the experiments conducted to date. While the inviscid panel code analysis shows significant thrust enhancement generated by the hind-wing, the experiment indicates that the hind-wing's viscous drag nullifies this additional thrust. However, it remains to be seen whether this conclusion still holds if the hind-wing also executes a flapping motion. Lan (1979) performed an inviscid vortex lattice analysis of two rectangular flapping wings in tandem arrangement and he showed that this dragonfly arrangement can produce high thrust with high efficiency if the pitching is in advance of the flapping and the hind-wing leads the fore-wing with some optimum phase angle. Recently, Jones and Platzer (2000) presented additional thrust measurement on the 6 gram micro-air vehicle configuration shown in Fig. 9. The measured static thrust values are in good agreement with the panel code prediction, but there is a significant decrease in thrust for increasing free-stream speeds, as seen
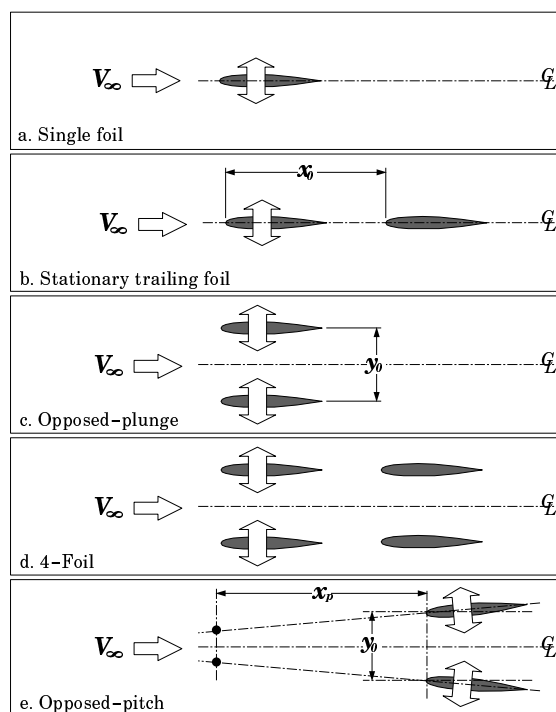

Fig. 7: Evaluated configurations.

in their Figs. 24 and 25. This discrepancy is likely to be caused by the shedding of leading edge vortices (dynamic stall). However, it is unclear why good thrust values are achieved at zero free-stream (in the presence of dynamic stall) and a rapid thrust loss occurs at small wind speeds. Flow visualizations and measurements are presently in progress to clarify the flow features which cause this loss of thrust.
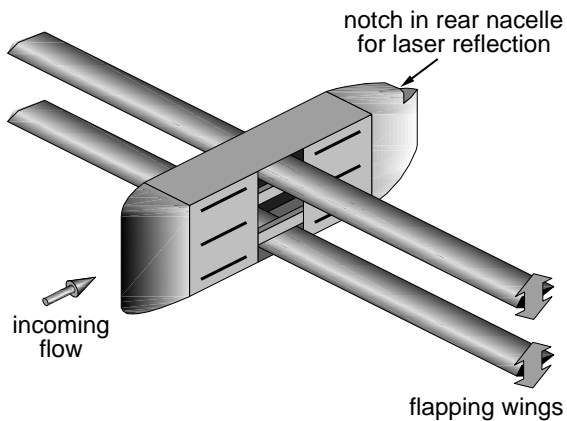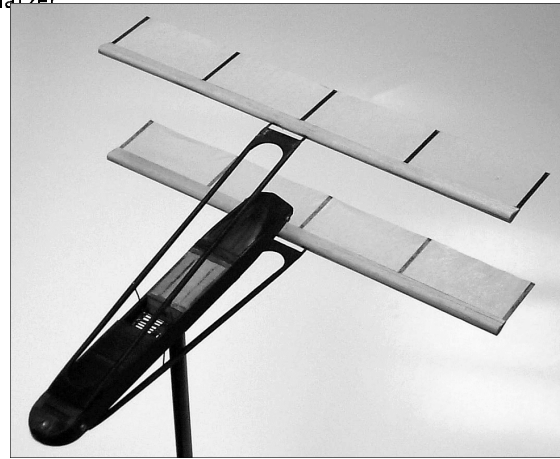
Fig. 8: Isometric view of the large model.

Fig. 9: Isometric view of the MAV.

Boundary Layer Propulsion

As shown in the previously described experiments and computations, a flapping foil is a device which generates a jet flow downstream of the trailing edge and imparts additional momentum to the flow. Hence the question arises whether small flapping foils can be used to energize a boundary layer flow or to prevent/delay flow separation. Lai, Yue, Platzer (1997), Dohring (1998), and Dohring *et al.* (1998) performed several experiments to explore the flow physics of foils flapping in a boundary layer or in a separated flow region.

Flow visualization studies, LDV measurements and Navier-Stokes computations were performed to determine the flow characteristics generated by a small foil which executes a sinusoidal plunge motion in a flat-plate boundary layer. It was found that the jet velocity generated downstream of the plunging foil increases with decreasing distance from the flat plate. The plunge amplitude, frequency and distance from the wall were varied quite systematically and it was found that there is an optimum spacing between plate and foil. The jet velocity could be almost doubled compared to the values measured in a free-stream. This finding is quite consistent with the previously mentioned favorable biplane interference effect where the two foils oscillate in counter-phase, simulating the ground effect. The measured and the Navier-Stokes computed velocity profiles downstream of the oscillating foil agree quite well, as shown for example in Fig. 8 of Dohring *et al.* (1998). Similarly, the dye visualizations of the vortical flow patterns could be reproduced quite well with the Navier-Stokes computations, as documented by Dohring (1998).

Flow Separation Control

In an experiment, a small plunging airfoil was mounted in the separated wake flow region of an airfoil which had a semi-circular or a cusped trailing edge. Complete flow re-attachment could be achieved by selecting the proper plunge amplitude and frequency. As shown by Dohring (1998) and Dohring *et al.* (1998), Fig. 14, the controlling parameter was again found to be the non-dimensional plunge velocity.

In a second experiment, the sinusoidally plunging foil was mounted in the recirculatory flow region caused by the flow over a backward-facing step. The experimental setup is shown in Fig. 1 of Lai *et al.* (1997). The extent of the separated flow region could be reduced by more than 60 percent by proper placement, frequency, and amplitude of the plunging foil, as shown in Figs. 9-12 *(Lai et al., 1997)*.

Finally, in a third series of experiments a small plunging foil was placed in the wake of a conventional airfoil. Lai and Platzer (1998) could show that the velocity defect in the wake could be substantially reduced, making the wake almost indistinguishable from the free-stream flow.

Vortex Structures Generated by Flapping Finite-Span Wings

Using a smoke-wire, streaklines near the centerline of the MAV are shown in Fig. 10 for a frequency of 10Hz and a velocity of $1.5m/s$, resulting in a reduced frequency of about 1.5. The

flow is remarkably planar, and the outline of a number of vortex structures can be seen. The wake topology predicted by the panel code for the same case is shown in Fig. 11, and is a pretty good representation of the real flow.

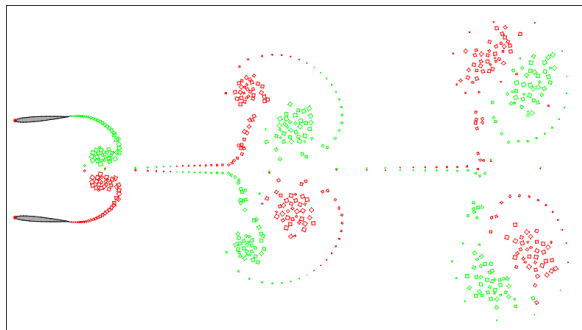*Fig. 10:* Centerline wake topology at $k = 1.5$.

Fig. 11: Panel-code prediction of the wake.

Note, the wake shown for the panel code is indicated using a small square to represent a discrete vortex shed from each airfoil at each time-step to apply the Helmholtz condition. The size of each square indicates its vorticity magnitude, and the color indicates its orientation. Therefore, the panel code is essentially a *vorticity tagging* approach, and provides excellent detail of the evolution of the shed vorticity, but provides no visualization information on the external flow. The streaklines, on the other hand, provide an excellent view of the external flow, but virtually no information within the vortical structures.

Away from the centerline the flow is highly three-dimensional. At low reduced frequencies the tip vortices develop and evolve somewhat independently from one and other, that is, the vorticity on each changes sign as the wings plunge sinusoidally. However, at higher frequencies the nature of the flow changes considerably. In Figs. 12 and 13 streaklines released about half a chord length outside of the wing tips are shown from a rear-quarter view and a top view, respectively. The flow-speed is $1.5m/s$, and the frequency is 20Hz, resulting in a reduced frequency of $k = 3.0$. The Strouhal number is difficult to estimate, due to the aeroelastic pitching of the wings, but it should be about 1.3.
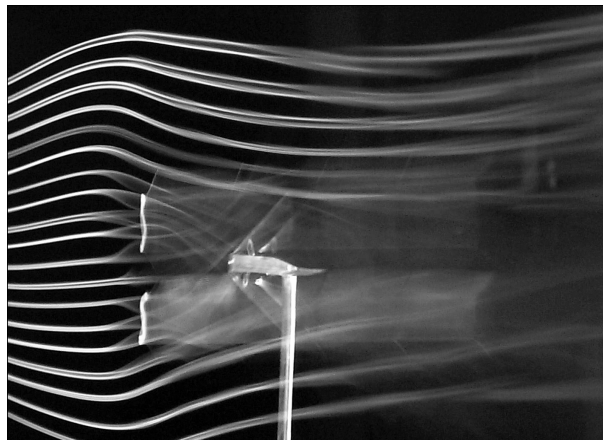

Fig. 12: Streaklines $0.5c$ outside of wing-tip.

The true nature of the flow is difficult to ascertain from Figs. 12 and 13. There appears to be massive flow entrainment from the sides, starting from about the leading edge of the wing. The four tip vortices do not appear to sinusoidally change sign, although their strength must fluctuate. Looking from behind, the left, upper vortex rotates counter-clockwise, and its

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core turns toward the centerline, and is then deflected upward as it approaches the centerline. The other three trailing vortices are symmetric. A sketch of the primary trailing vortex structures is shown in Fig. 14.
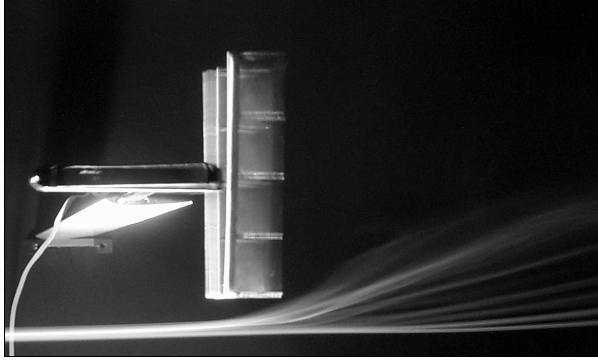

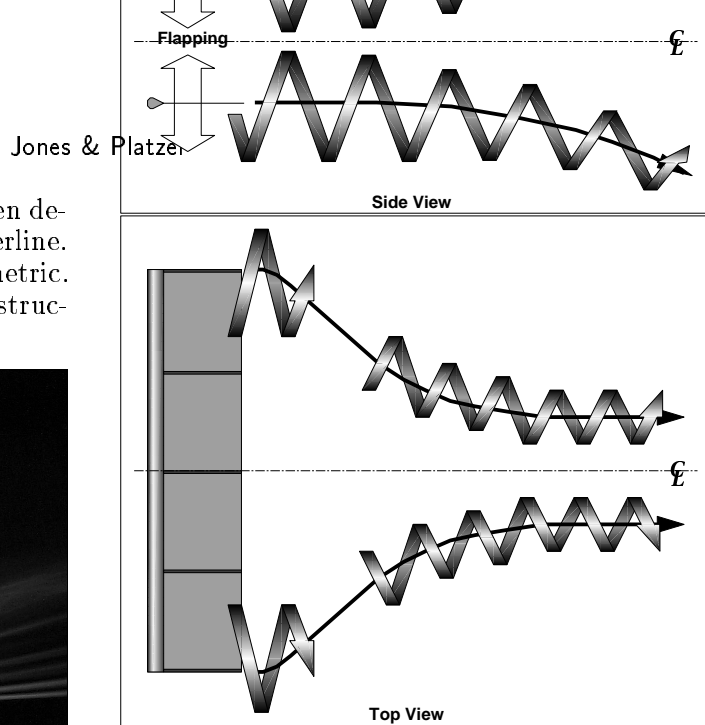*Fig. 13:* Streaklines 0.5c outside of wing-tip.

Fig. 14: Primary vortex structures.

Current computational investigations are underway using a three-dimensional, unsteady panel method to model this flow. Any such inviscid flow calculation cannot account for flow-separation effects from the leading edge, yet it is likely that significant dynamic stall effects do occur. Therefore, the experimental studies currently underway are aimed at identifying the significance and extent of the dynamic stall effects, and whether or not they can be beneficial with proper tuning of the motion.

Summary

The experiments described in this paper show that the aerodynamic characteristics of single foils and foil combinations can be predicted reasonably well with inviscid panel codes as long as no significant vortex shedding (dynamic stall) occurs from the leading edges. However, typical micro-air and sea vehicles are likely to operate in a Reynolds number, flapping-frequency and amplitude range where separation from the leading edge is inevitable. Further experimental and computational studies are required to understand this type of flow and to find the parameter combination for optimum thrust. The biplane arrangement appears to be a promising configuration for the propulsion of micro-air vehicles. Indeed, the tests completed to date show that sufficient thrust can be generated for hovering flight.

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