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# The Unsteady Aerodynamics of Flapping-Foil Propellers

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Platzer, M.F. and Jones, K.D., "The Unsteady Aerodynamics of Flapping-Foil Propellers,"  
Proceedings of the 9th International Symposium on Unsteady Aerodynamics, Aeroacoustics



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# THE UNSTEADY AERODYNAMICS OF FLAPPING-FOIL PROPELLERS

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**Abstract.** It is the objective of this paper to summarize the authors' recent work on flapping foils. Water tunnel experiments on sinusoidally plunging foils are described which elucidate the change in vortical wake pattern shed from the foil's trailing edge. These experiments were carried out using dye flow visualization and laser-Doppler velocimetry. It is found that the wake pattern is a strong function of the maximum non-dimensional plunge velocity, with the wake topology changing from a typical Kármán vortex street to an inverse Kármán vortex street to an asymmetric wake structure as the non-dimensional plunge velocity increases. These results are partly reproducible with inviscid panel code and Navier-Stokes code predictions. Additional interesting features are obtained if two degrees of freedom are permitted (pitch-plunge motions). Depending on the pitch/plunge amplitudes and the phasing between the two motions, the foil either produces thrust or extracts energy. A water tunnel experiment is described which demonstrates the possibility of power generation from a slowly flowing, shallow river. Additional interesting features are found if two airfoils in close proximity to each other are studied. Experiments with two airfoils arranged in a biplane configuration and oscillating in counter-phase show significant thrust and propulsive benefits in comparison to single flapping foils.

## 1. Introduction

Bird flight and aquatic animal propulsion have fascinated many people for a long time. However, the lack of immediately apparent commercial or military applications has kept the funding level of studies devoted to these

problems relatively low. It appears that there is an increasing interest in the development of micro air and water vehicles which, in turn, raises the question whether *unconventional* propulsion systems, such as those used by birds and aquatic animals for millions of years, deserve a *second look*.

The first explanation of the bird's ability to generate a thrust force by means of flapping its wings seems to have been published by Knoller (1909) in Vienna and Betz (1912) in Göttingen, in independent studies. Prandtl's student Birnbaum (1924) first presented a solution for incompressible flow past flapping airfoils, while Katzmayer (1922) in Vienna produced the first wind tunnel measurements which conclusively showed that an airfoil mounted in an oscillating wind stream experiences a thrust force. Garrick (1936) applied Theodorsen's theory (Theodorsen, 1935) to the problem of sinusoidally plunging and/or pitching airfoils and presented results valid for the whole reduced frequency range. In the 1940's and 50's Schmidt (1965) in East Germany started to conduct systematic experiments on flapping foil propellers which led him to the development of his tandem configuration, that he coined the *wave propeller*, and its demonstration on a catamaran boat.

Theodorsen's oscillatory thin airfoil theory (Theodorsen, 1935), as applied by Garrick (1936), shows that the propulsive efficiency of a single harmonically plunging airfoil is only about 50 percent unless the airfoil oscillates rather slowly (which in turn requires a large airfoil in order to obtain significant thrust values). Schmidt sought to overcome this deficiency by arranging two airfoils in tandem, where the forward foil is oscillating and the rear-ward foil is stationary. This makes it possible to convert the vortical energy generated by the forward foil into additional thrust rather than being wasted. Schmidt claimed that his *wave propeller* achieved efficiencies comparable to those of conventional propellers and had the additional advantage of enabling operation in shallow waters.

The only predictive tool available to Schmidt was Theodorsen's inviscid oscillatory thin airfoil theory - a tool of only marginal utility for his tandem wing configuration. Therefore, he arrived at his *wave propeller* by pure experimentation. Future progress in the design and development of *unconventional* propellers will depend on a better understanding of the flow physics of such propellers and on the acquisition of reliable aerodynamic design data. This requires the systematic measurement and computation of the flow over flapping single foils and foil combinations.

It is the purpose of this paper to review our work on this problem over the past few years, to assess the current state-of-the-art, to point out discrepancies and deficiencies in our present understanding of flapping foil aerodynamics, and to indicate needs for future investigations.

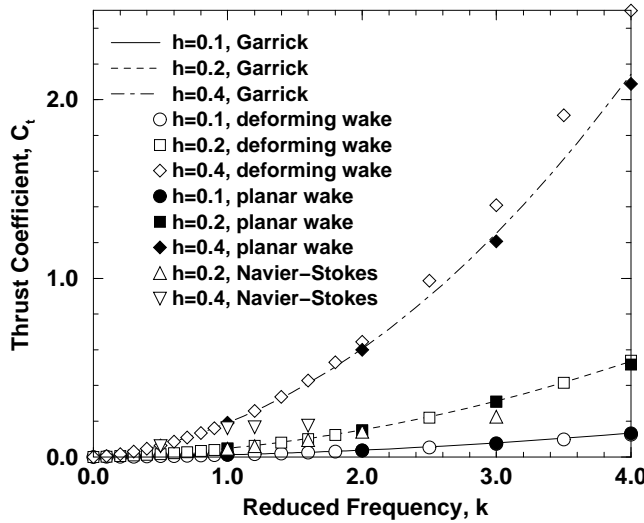


Figure 1. Thrust versus  $h$ ,  $k$  and wake model for a plunging airfoil.

## 2. Single Flapping Foils

Inviscid, oscillatory, thin-airfoil theory leaves many important questions unanswered. Among them are the effect of flapping amplitude, airfoil geometry, and most importantly, viscous flow effects, especially at the small Reynolds numbers encountered by micro air and water vehicles. Any improved prediction method must be validated by well controlled experiments. In this paper we limit ourselves to the discussion of two-dimensional flows.

Garrick, using thin-airfoil theory, showed that both pitching and plunging airfoils develop a thrust force. The dependence of thrust and propulsive efficiency on the non-dimensional plunge amplitude and reduced frequency is shown in Figs. 1 and 2, where the predictions of the panel code are compared with Garrick's theory.

Note, Garrick's theory treats the airfoil as a flat plate and confines the wake vorticity to the plane of the airfoil. The panel code, on the other hand, uses airfoils of finite thickness (a NACA 0012 in this case), and employs a deforming wake model. If we restrict the shed vorticity to the plane of the airfoil in the panel code, following Garrick's linear approach, the two methods agree well, demonstrating that airfoil thickness has little effect on the inviscid performance, but accurate wake modeling does. The Navier-Stokes predictions of Tuncer *et al.* (1998) are also included in Figs. 1 and 2, as well, providing some insight into the losses associated with flow separation, to be discussed in more detail later.

The performance for pitching airfoils is shown in Fig. 3. It is seen that

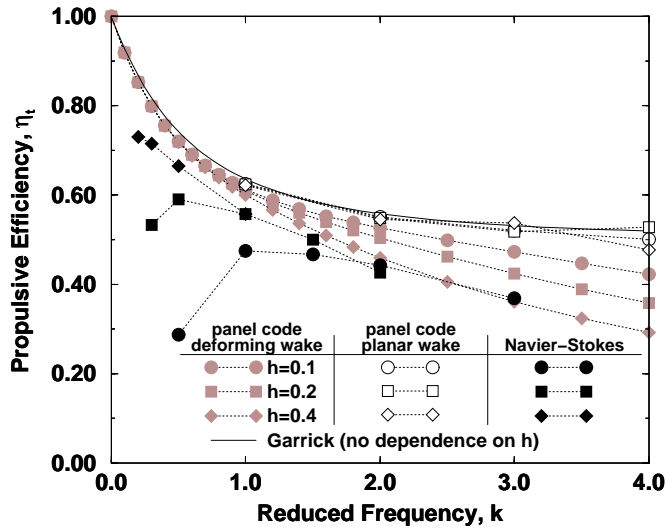


Figure 2. Efficiency versus  $h$ ,  $k$  and wake model for a plunging airfoil.

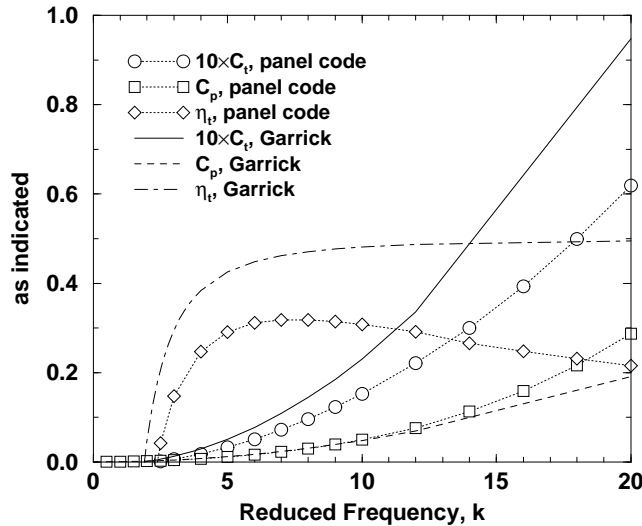


Figure 3. Performance versus  $k$  for a pitching airfoil.

drag, not thrust, occurs at a low frequency for pitching airfoils, whereas plunging foils develop thrust over the whole frequency range. However, for plunging airfoils note that both the thrust and the power-required tend toward zero as the frequency decreases, resulting in efficiency values approaching unity. It is therefore of interest to assess the validity of this prediction against available measurements. To this end it is important to

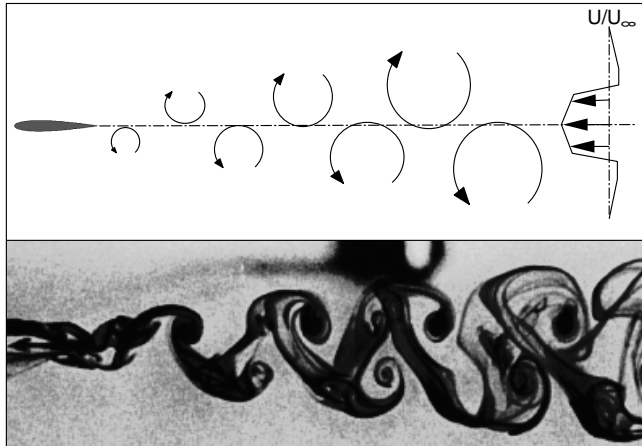


Figure 4. Drag-indicative vortex street (Jones *et al.*, 1998).

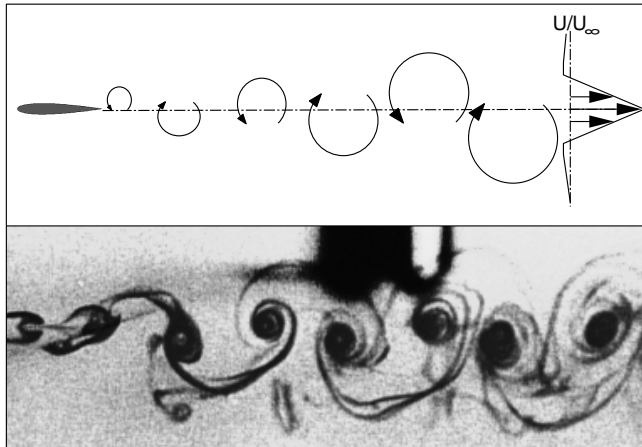


Figure 5. Thrust-indicative vortex street (Jones *et al.*, 1998).

recognize the difference between drag-indicative and thrust-indicative vortical wake patterns shed from flapping foils. The two wake patterns are shown in Figs. 4 and 5 (Jones *et al.*, 1998).

Kármán vortex streets, shown in Fig. 4, produce a time-averaged velocity distribution with a distinct velocity deficit, indicative of drag. Reverse Kármán vortex streets, shown in Fig. 5, with counterclockwise upper vortices and clockwise lower vortices, produce a time-averaged jet-type velocity distribution, indicative of thrust.

Koochesfahani (1989) visualized the vortices shed from a NACA 0012 airfoil pitching sinusoidally about its quarter chord point. He also obtained

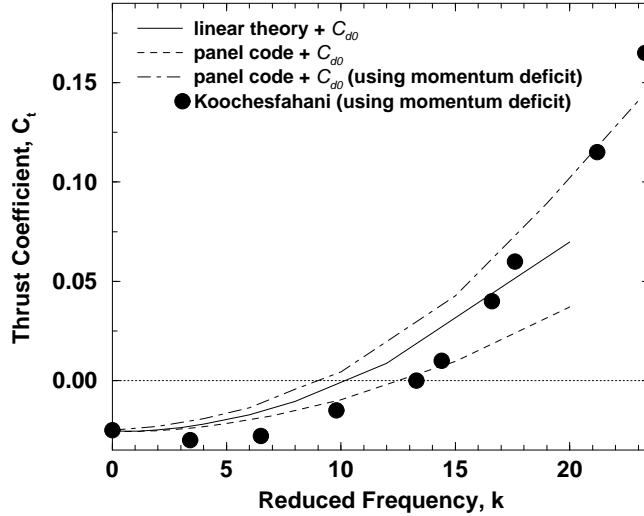


Figure 6. Thrust comparison for pitching airfoils.

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. His measured thrust is compared to linear theory and the panel code in Fig. 6. We refer to our discussion of this problem in Jones *et al.* (1998).

Lai and Platzer (1999) visualized and measured the vortical wakes shed from harmonically plunging NACA 0012 foils, using dye flow visualization and LDV for the measurement of the time-averaged velocity profiles. Similar to Koochesfahani, the tests were conducted in water at freestream speeds ranging from 0.05 to 0.21 m/sec, corresponding to Reynolds numbers from 500 to 20100. The amplitude/chord ratio,  $h$ , and the frequency of the plunge oscillation were varied between 0 and 0.1 and 0 and 10 Hz, respectively. It was found that a good parameter to categorize the resulting phenomena is the product of the amplitude/chord ratio and the reduced frequency, representing the maximum plunge velocity-to-freestream speed ratio, or the maximum non-dimensional plunge velocity, which for pure plunge motions is the Strouhal number times  $\pi$ . The changes in observed vortex patterns as this speed ratio is increased is shown schematically in Fig. 7 of Lai and Platzer (1999). For zero and very low ratios the Kármán vortex street is observed which changes to the reverse Kármán street at values of approximately 0.3 and to a deflected street at values of approximately 1. For actual pictures of the vortex patterns we refer to Figs. 3, 4 and 5

of Lai and Platzer (1999). The LDV-measured time-averaged velocity profiles show that the maximum streamwise velocity measured downstream of the trailing edge starts to exceed the freestream speed as soon as the non-dimensional plunge velocity exceeds 0.25.

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 is clear that drag is generated at speed ratios less than 0.25. It is therefore interesting to compare the measurements with Navier-Stokes computed force values. The thrust and propulsive efficiency predicted by a Navier-Stokes code for a plunging airfoil is shown in Figs. 1 and 2, taken from Tuncer and Platzer (1996) for the sinusoidally plunging NACA 0012 airfoil at a chord-Reynolds number of 3 million. It is seen that thrust is predicted for all values of amplitude and frequency down to vanishingly small values. This prediction disagrees with the experimental findings. However, it must be noted that these Navier-Stokes calculations account only for the pressure drag and not for the viscous drag. Clearly, at low amplitudes and frequencies the viscous effects are dominant. Linear theory and Navier-Stokes predictions are in good agreement for small amplitude values. 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.

Another interesting comparison can be made by using the inviscid panel code described by Platzer *et al.* (1993). This code accounts for the effect of airfoil geometry and vortex roll-up. Plotting the measured wake wave lengths as a function of plunge amplitude and frequency one obtains the results shown in Figs. 10 and 11 of Jones *et al.* (1998). It is seen that the wave length increases with increasing amplitude of oscillation, an effect which is reasonably well predicted by the panel code. On the other hand, the wave length decreases with frequency for a given amplitude. Again, the panel code predicts the experimental observations quite well. The panel code can also be used for a direct comparison with the measured time-averaged velocity profiles, as shown in Figs. 7, 8 and 9 (Jones *et al.*, 1998). For the two lower non-dimensional plunge velocities the agreement is quite good. For a plunge velocity of 2.3 there is a highly deflected vortex wake and the panel code prediction is marginal. However, it is remarkable that the panel code correctly predicts the phenomenon of the asymmetric vortex pattern, as shown in Fig. 10 (Jones *et al.*, 1998). Further work is necessary to clarify whether the measured profiles in this case are exclusively caused by the shedding of trailing edge vortices or by a combination of leading and



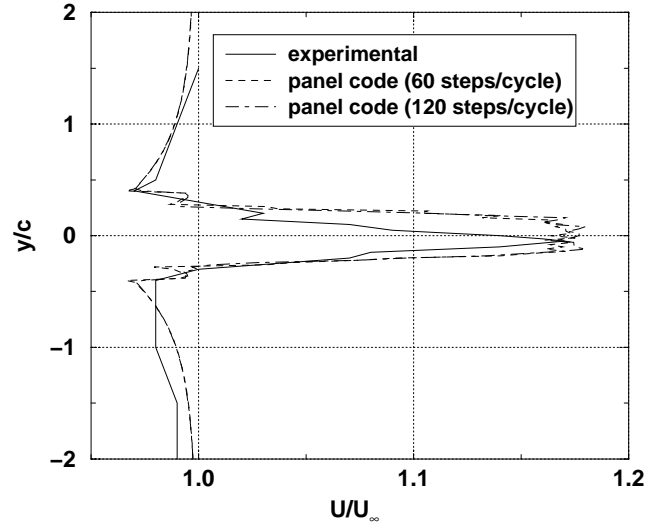


Figure 7. Time-averaged velocity profiles for  $hk = 0.37$  (Jones *et al.*, 1998).

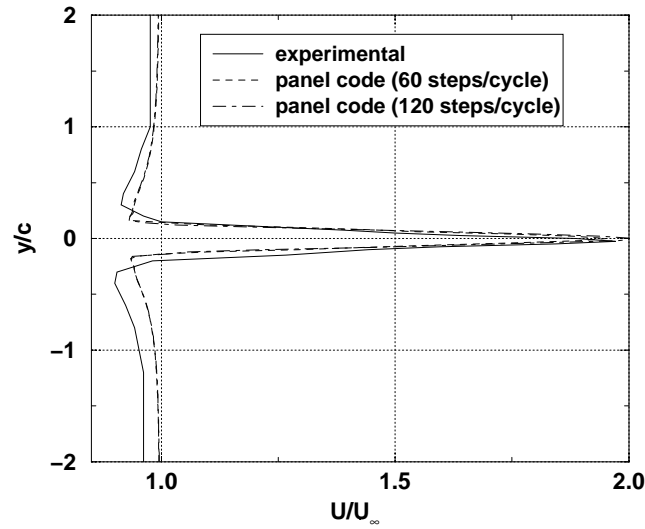


Figure 8. Time-averaged velocity profiles for  $hk = 0.60$  (Jones *et al.*, 1998).

trailing edge vortices.

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. By fixing the product of  $h$  and  $k$  while varying their ratio, the induced angle of attack (and the Strouhal number) are fixed but, as shown in Figs. 11

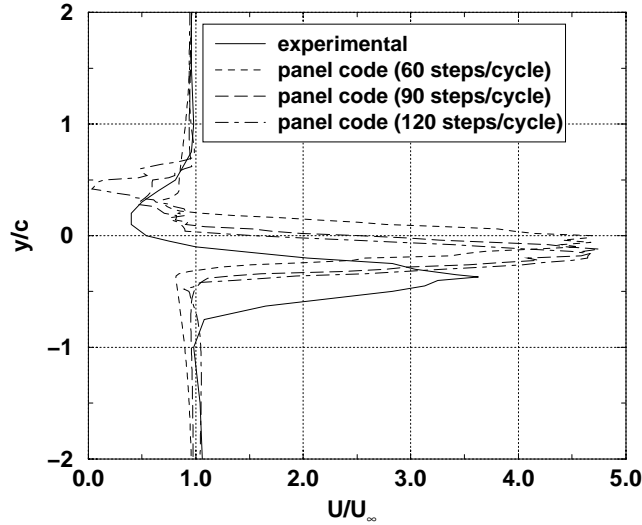


Figure 9. Time-averaged velocity profiles for  $hk = 2.30$  (Jones *et al.*, 1998).

and 12, the performance changes dramatically, greatly favoring the high amplitude low frequency case. In Fig. 11 the wake topologies computed by the panel code are shown for three simulations of a NACA 0012 airfoil, flapping with the same Strouhal number, 0.032 ( $hk = 0.1$ ), but with different reduced frequencies. The three plots are scaled by the wake-wavelength ( $\lambda = 2\pi/k$ ), with the vertical lines indicating the wake periods. The wake width (in terms of  $\lambda$ ) and non-linearity (roll-up) increase with increasing  $k$ . The effect this has on the performance is plotted in Fig. 12, where the predictions of Garrick's linear theory are plotted against results from the panel code and the Euler code. The Euler code simulations are at  $M_\infty = 0.3$ , and the static drag has been subtracted.

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 (included here as Fig. 13), 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.

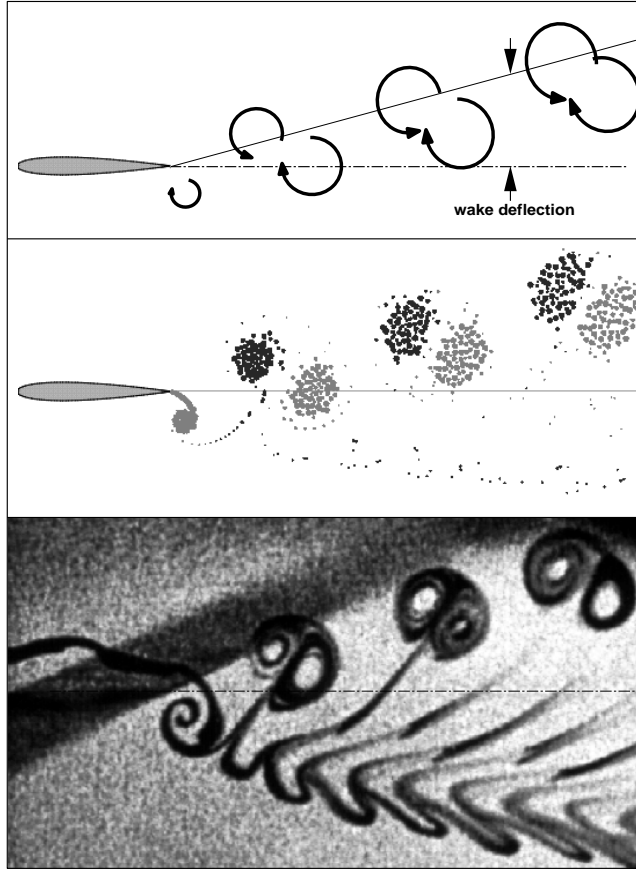


Figure 10. Experimental and numerical wakes for  $hk = 1.5$  (Jones *et al.*, 1998).

### 2.1. COMBINED PITCH/PLUNGE MOTION

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. 14. 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). Using the panel code, thrust, power, and propulsive efficiency can be

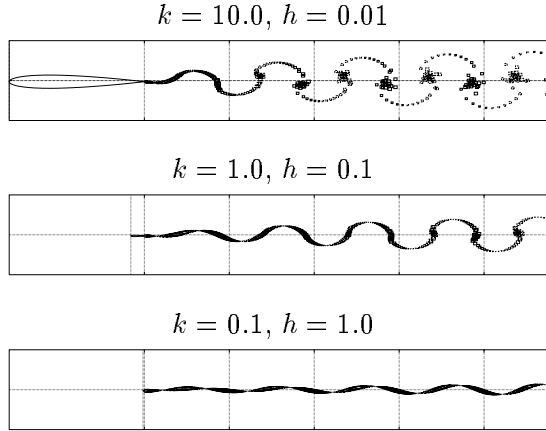


Figure 11. Dependence of wake stability on  $h$  and  $k$  ( $hk = 0.1$ ).

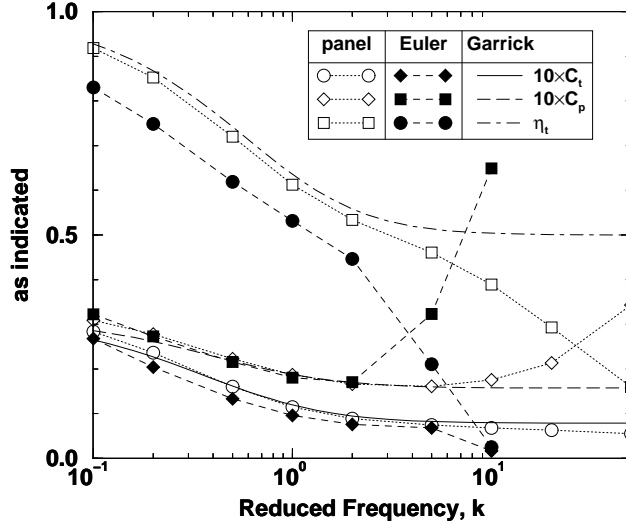


Figure 12. Dependence of performance on  $h$  and  $k$  ( $hk = 0.1$ ).

studied as a function of phasing between pitch and plunge. This is shown in Figs. 15 and 16 (Jones and Platzer, 1997). It is seen that for the parameter combination chosen in Fig. 15 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. 16, power is extracted for phase angles near 90 degrees at both the highest efficiency and maximum power extraction. These findings are consistent with earlier

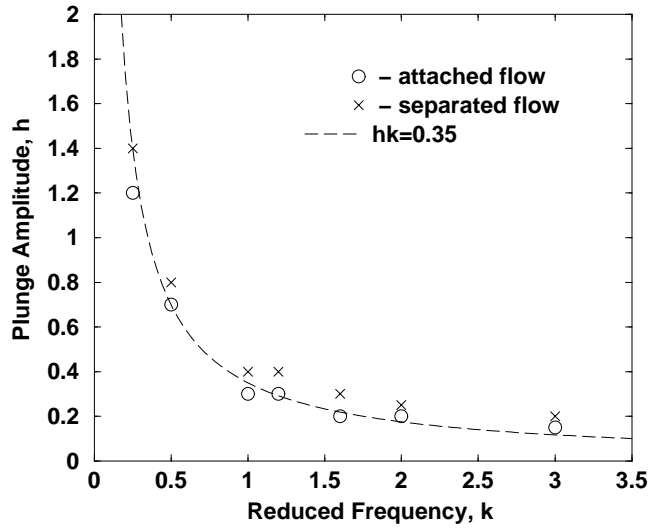


Figure 13. Separation behavior of a plunging NACA 0012,  $Re=3 \times 10^6$ .

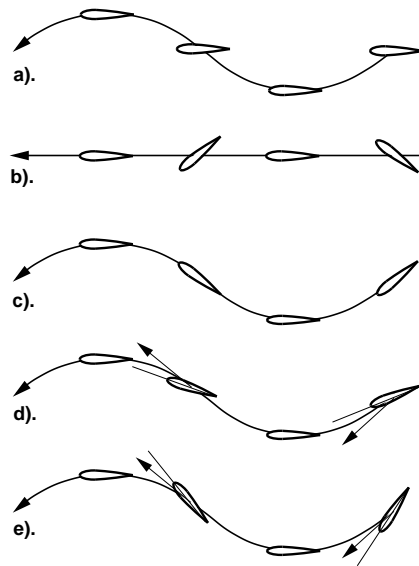


Figure 14. Effective versus geometric angle of attack.

results obtained by Lan (1979) for a rectangular wing of aspect ratio 8 using an unsteady quasi-vortex-lattice method.

The predictive power of any inviscid flow theory needs to be evaluated by comparison with direct measurements of the thrust generated by flapping wings. Anderson *et al.* (1998) presented thrust and power mea-

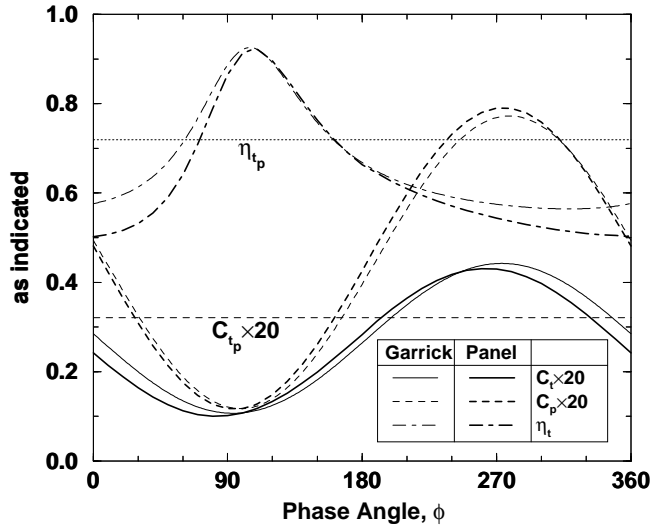


Figure 15. Performance for  $k = 0.5$ ,  $h = 0.2$  and  $\Delta\alpha = 4^\circ$ .

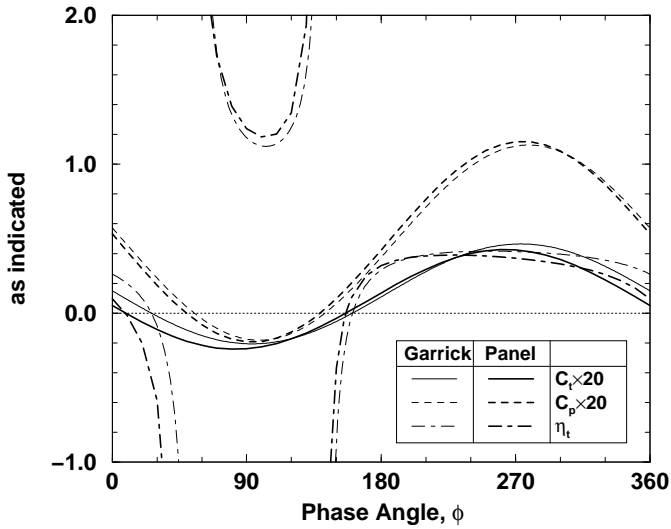


Figure 16. Performance for  $k = 0.5$ ,  $h = 0.2$  and  $\Delta\alpha = 8^\circ$ .

measurements for a NACA 0012 airfoil executing combined plunge and pitch motions at a Reynolds number of 40000 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.

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 *et al.* (1999) 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.

## 2.2. STATIC THRUST

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 be-

cause 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.

### 3. 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 aerodynamics and 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 Katzmayer 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. Platzner *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. 17 (b) and (c), 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 Platzner (1999) performed a more detailed computational and experimental investigation of both arrangements. To this end the model shown in Fig. 18 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. 17 (d).

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



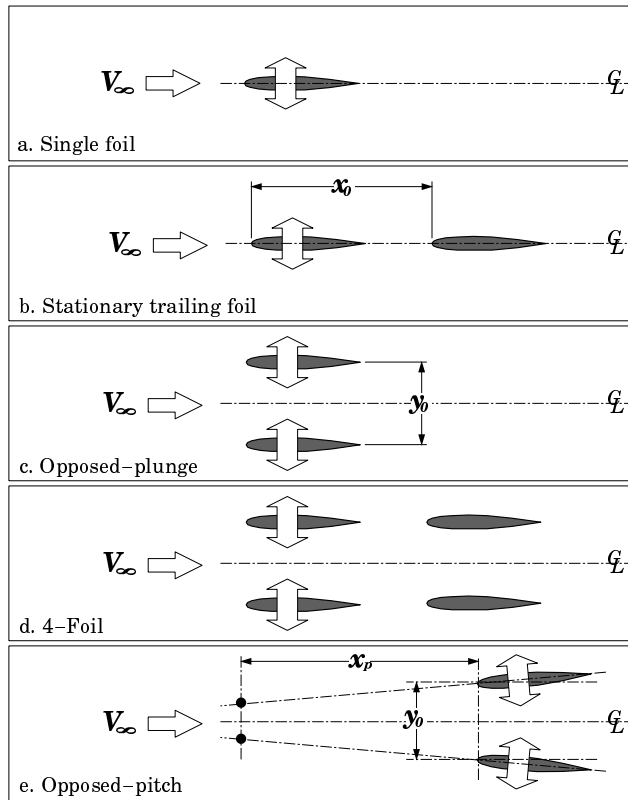


Figure 17. Numerical and experimental configurations.

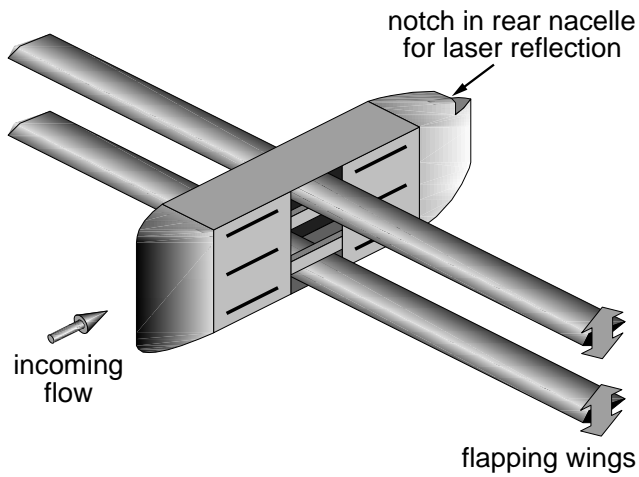


Figure 18. Large experimental flapping mechanism.

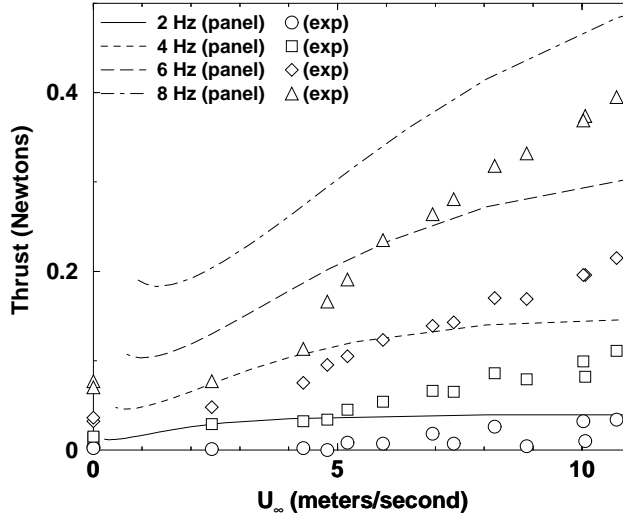


Figure 19. Thrust for pure plunge motion of configuration (c).

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. 19 taken from 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 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. 20. 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 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.

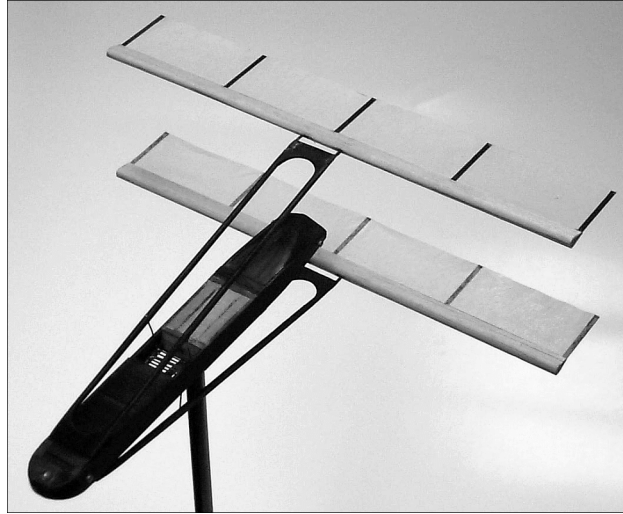


Figure 20. Micro air vehicle test model with 15cm span and 6g mass.

#### 4. Flapping-Foil Power Generators

The possibility of energy transfer from the air to a vibrating wing was first revealed in a number of flutter incidents on military aircraft in World War I. The need to avoid this dangerous phenomenon has inspired the development of comprehensive analysis methods for the incompressible flow over oscillating airfoils, starting with Birnbaum (1924) and perfected by Theodorsen (1935) in the United States and Küssner (1936) in Germany. It is now well recognized that single-degree-of-freedom flutter of an airfoil in the pure-plunge mode cannot occur in attached incompressible flow, but single-degree-of-freedom pitching-mode (torsional) flutter is already a distinct possibility. This type of flutter was first analyzed in some detail by Smilg (1949) using Theodorsen's flat-plate theory. More recently, Jones and Platzer (1996) investigated the influence of airfoil geometry on torsional flutter using the unsteady panel code of Platzer *et al.* (1993). The probability of encountering explosive flutter is dramatically increased if the airfoil can oscillate in a combined pitch and plunge mode. This type of flutter can easily be demonstrated by the *flutter engine* described by Duncan (1958). If the airfoil is forced to oscillate in such a way that the pitch oscillation leads the plunge oscillation by approximately 90 degrees, violent flutter is induced at a sufficiently high wind-tunnel speed. Although this possibility of energy transfer and power generation has been known for many years, little work has been done in the past to exploit this possibility.

Figure 16 was obtained using the previously mentioned unsteady panel

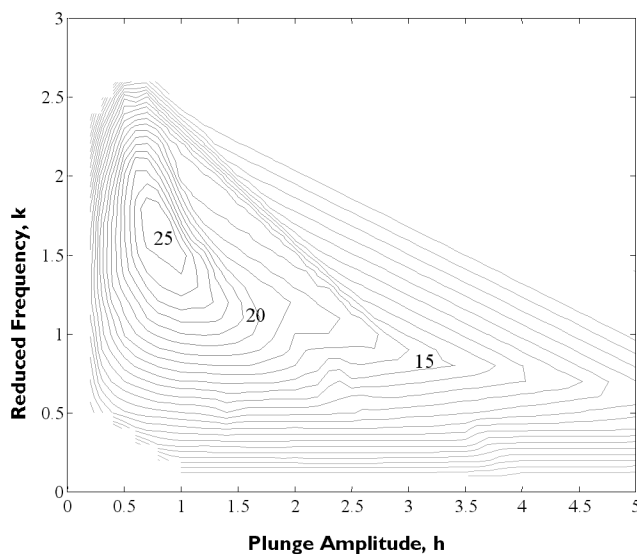


Figure 21. Total power extraction efficiency of a wingmill for  $\alpha_e < 15^\circ$  and  $\phi = 90^\circ$ .

code. It confirms that power can be extracted from the flow if the combined pitch and plunge oscillation occurs with a positive effective angle of attack at phase angles around 90 degrees. Davids (1999) used this code to analyze the various parameters which affect wingmill performance. He found that the optimum total power extraction efficiency occurs for a non-dimensional plunge amplitude of approximately 0.8 and a reduced frequency of approximately 1.7 if the phase angle is held at 90 degrees and the effective angle of attack at 15 degrees, where the total power extraction coefficient, following the convention adopted by the wind-energy community, is the ratio of the power extracted to the total power available in the control volume. This is shown in Fig. 21.

McKinney and DeLaurier (1981) performed wind-tunnel tests of an oscillating-wing windmill (which they termed *wingmill*). Jones *et al.* (1999) applied the unsteady panel code to their wingmill test conditions and found reasonably good agreement with their results, as shown in Fig. 22. In this figure, the ideal efficiency is defined as the ratio of the power extracted to the ideal power available, where the ideal power is based on actuator disc theory showing that at most  $16/27$  of the power flowing through the control volume can be extracted. The coefficient  $16/27$  is referred to as the Betz coefficient.

Jones *et al.* (1999) also built and tested a wingmill in one of the Naval Postgraduate School water tunnels. The model was designed to span the tunnel and provide plunge amplitudes of up to twice the chordlength and

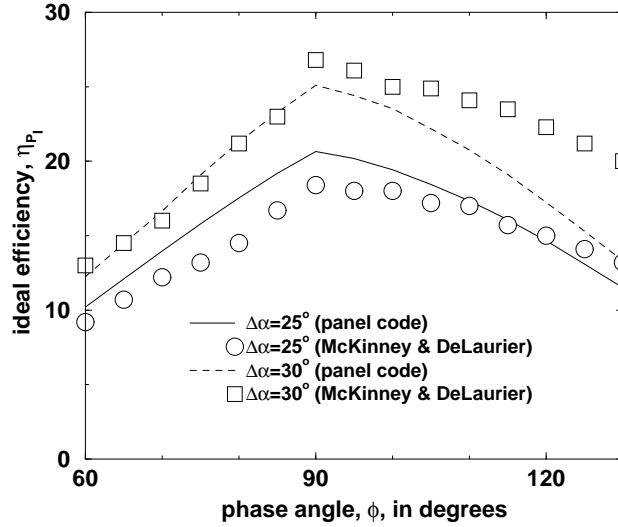


Figure 22. Ideal power extraction efficiency; panel code versus experiment.

pitch amplitudes up to 65 degrees. The model is shown in Figs. 23 and 24. The wingmill performed quite satisfactorily, but further work is required to achieve optimum operating conditions. Detailed test results are found in Davids (1999).

## 5. Dynamic Airfoil Stall

The above described studies clearly show that the performance of flapping foil propellers and power generators may be severely limited by the onset of dynamic airfoil stall. On the other hand, the experiments of Anderson *et al.* (1998) and the calculations of Ramamurti *et al.* (1999) indicate that dynamic stall may have beneficial effects under certain operating conditions. It is therefore critical to understand and predict the dynamic stall phenomenon. Fortunately, because of its occurrence on helicopter and compressor blades and on aircraft wings much experimental and computational work has been devoted to this problem and we refer to the review papers by Carr (1988), Carr and Chandrasekhara (1996) and Ekaterinaris and Platzer (1997). Most experiments and analyses were performed for airfoils experiencing dynamic stall in the pure pitch motion. The most instructive and comprehensive tests of pitching airfoils are those of Chandrasekhara and Carr (1990) and Chandrasekhara and Ahmed (1991), carried out in the Reynolds number range half to one million. They identified the formation and eventual bursting of a separation bubble preceding the formation of the dynamic stall vortex on the NACA 0012 airfoil. This sequence of

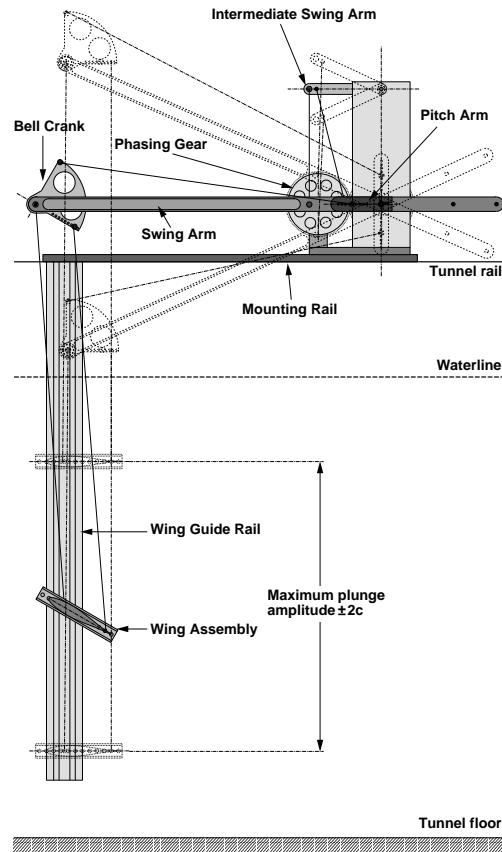


Figure 23. Flutter engine - side view.

events could be predicted to some extent using a Navier-Stokes analysis in combination with proper modeling of the boundary layer transition phenomenon, as shown by VanDyken *et al.* (1996). However, the prediction of the flow reattachment process still presents enormous difficulties. In the low Reynolds number range between 5,000 to 10,000 Mehta and Zalman (1975) and Mehta (1977) presented a laminar Navier-Stokes calculation for a pitching airfoil. Ghia *et al.* (1991, 1992) compared their Navier-Stokes calculations with the previous computations of Mehta and the experimental studies of Walker *et al.* (1985) at Reynolds numbers of 10,000 and 45,000. Ghosh Choudhuri *et al.* (1994) studied the initial stages of two-dimensional unsteady leading-edge boundary layer separation of laminar flow over a pitching NACA 0012 airfoil at a Reynolds number of 10,000. Unfortunately, no detailed flow visualizations or measurements similar to Chandrasekhara's experiment are as yet available to validate these numeri-

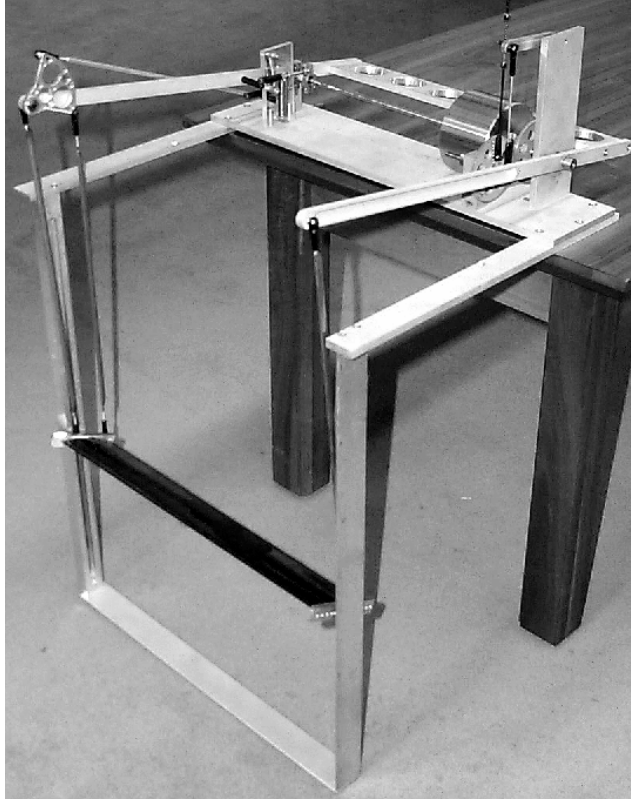


Figure 24. Flutter engine - photograph.

cal predictions. An even greater dearth of detailed experimental information exists about the dynamic stall flow physics on airfoils in pure plunge motion or in combined pitch/plunge motion. Further work complementing the experiments of Anderson *et al.* (1998) are needed. Similarly, further Navier-Stokes computations extending the cases studied by Tuncer *et al.* (1998), Isogai *et al.* (1999) and Ramamurti *et al.* (1999) are required. Experimental and computational investigations are currently being conducted by the authors using the above described flapping wing models together with further Navier-Stokes calculations.

## 6. Summary

In this paper we attempted to summarize the current knowledge about the unsteady aerodynamic and propulsive characteristics of flapping single foils and foil combinations. It is apparent that the vortical wakes shed from flapping foils are a strong function of the non-dimensional plunge ve-

locity (Strouhal number  $\times \pi$ ), changing from drag-indicative wakes at low plunge velocity to thrust-indicative symmetrical wakes and to asymmetric thrust/lift-indicative wakes with increasing plunge velocity. The flow visualizations, LDV measured time-averaged wake velocity profiles and the direct thrust measurements are predicted well with the panel and Navier-Stokes codes for thrust-indicative symmetric wakes shed from foils in pure plunge oscillation. At low plunge velocities the prediction of the unsteady aerodynamic characteristics is quite difficult because the viscous effects are dominant. The change from a symmetric wake to an asymmetric one is predicted both by the panel and the Navier-Stokes code. However, further experimental and computational work is required to clarify the question of how much vorticity shed from the leading edge contributes to this.

Considerable insight could be gained about the merits of using two foils. The tandem arrangement, used in Schmidt's *wave propellers*, where the upstream foil is oscillating and the downstream foil is stationary, appears to be relatively unattractive. The inviscid panel code analysis shows improved efficiency, but the inclusion of the viscous effects nullifies this advantage. On the other hand, the biplane arrangement offers considerable benefits in optimizing achievable thrust and efficiency compared to the single foil. However, it remains to be studied whether the dragonfly arrangement, where both the upstream and downstream foils are oscillating, is superior.

Flapping foils can be used either for thrust generation or energy extraction. The latter possibility has received little attention. However, it appears that flapping foils offer some attractive features for hydro power generation which deserve further exploration.

The performance of flapping-foil propellers and turbines may be limited or enhanced by the onset of dynamic stall. The detailed understanding and prediction of the dynamic stall phenomenon therefore is critical for the application of flapping-foil propellers on micro-air vehicles and power generators.

## 7. Acknowledgments

The authors would like to acknowledge the Office of Naval Research, the Naval Research Laboratory and the Naval Postgraduate School for support on these research efforts.

## References

- Anderson, J. M., Streitlien, K., Barrett, D. S. and Triantafyllou, M. S. (1998) Oscillating Foils of High Propulsive Efficiency, *Journal of Fluid Mechanics*, **Vol. 360**, pp. 41-72.  
Betz, A. (1912) Ein Beitrag zur Erklärung des Segelfluges, *Zeitschrift für Flugtechnik und Motorluftschiffahrt*, **Vol. 3**, pp. 269-272.



- Birnbaum, W. (1924) Der Schlagflügelpropeller und die kleinen Schwingungen elastisch befestigter Tragflügel, *Zeitschrift für Flugtechnik und Motorluftschiffahrt*, **Vol. 15**, pp. 128-134.
- Bosch, H. (1978) Interfering Airfoils in Two-Dimensional Unsteady Incompressible Flow, AGARD CP-227, Paper No. 7.
- Carr, L. (1988) Progress in Analysis and Prediction of Dynamic Stall, *Journal of Aircraft*, **Vol. 25, No. 1**, pp. 6-17.
- Carr, L. W. and Chandrasekhara, M. S. (1996) Compressibility Effects on Dynamic Stall, *Progress in Aerospace Sciences*, **Vol. 32**, pp. 523-573.
- Chandrasekhara, M. S. and Ahmed, S. (1991) Laser Velocimetry Measurements of Oscillating Airfoil Dynamic Stall Flow Field, AIAA Paper No. 91-1799.
- Chandrasekhara, M. S. and Carr, L. W. (1990) Flow Visualization Studies of the Mach Number Effects on Dynamic Stall of an Oscillating Airfoil, *Journal of Aircraft*, **Vol. 27, No. 6**, pp. 516-522.
- Dauids, S. T. (1999) A Computational and Experimental Investigation of a Flutter Generator, Master's Thesis, Dept. of Aeronautics and Astronautics, Naval Postgraduate School, Monterey, CA.
- Duncan, W. J. (1958) *Manual on Aeroelasticity, Volume I, Introductory Survey*, AGARD, pp. 1-51.
- Ekaterinaris, J. A. and Platzer, M. F., (1997) Computational Prediction of Airfoil Dynamic Stall, *Progress in Aerospace Sciences*, **Vol. 33**, pp. 759-846.
- Garrick, I. E. (1936) Propulsion of a Flapping and Oscillating Airfoil, NACA Report 567.
- Ghia, K. N., Yang, J., Osswald, G. A. and Ghia, U. (1991) Study of the Dynamic Stall Mechanism Using Simulation of Two-Dimensional Navier-Stokes Equations, AIAA Paper No. 91-0546.
- Ghia, K. N., Yang, J., Osswald, G. A. and Ghia, U. (1992) Study of the Role of Unsteady Separation in the Formation of Dynamic Stall Vortex, AIAA Paper No. 92-0196.
- Ghosh Choudhuri, P., Knight, D. D. and Visbal, M. R. (1994) Two-Dimensional Unsteady Leading-Edge Separation on a Pitching Airfoil, *AIAA Journal*, **Vol. 32, No. 4**, pp. 673-681.
- Isogai, K., Shinmoto, Y. and Watanabe, Y. (1999) Effects of Dynamic Stall on Propulsive Efficiency and Thrust of a Flapping Airfoil, *AIAA Journal*, **Vol. 37, No. 10**, pp. 1145-1151.
- Jones, K. D. and Platzer, M. F. (1996) Time-Domain Analysis of Low-Speed Airfoil Flutter, *AIAA Journal*, **Vol. 34, No. 5**, pp. 1027-1033.
- Jones, K. D. and Platzer, M. F. (1997) Numerical Computation of Flapping-Wing Propulsion and Power Extraction, AIAA Paper No. 97-0826.
- Jones, K. D., Dohring, C. M. and Platzer, M. F. (1998) Experimental and Computational Investigation of the Knoller-Betz Effect, *AIAA Journal*, **Vol. 36, No. 7**, pp. 1240-1246.
- Jones, K. D. and Platzer, M. F. (1999) An Experimental and Numerical Investigation of Flapping-Wing Propulsion, AIAA Paper No. 99-0995.
- Jones, K. D., Dauids, S. and Platzer, M. F. (1999) Oscillating-Wing Power Generator, ASME Paper No. FEDSM99-7050.
- Jones, K. D. and Platzer, M. F. (2000) Flapping-Wing Propulsion for a Micro Air Vehicle, AIAA Paper No. 2000-0897.
- Katzmayr, R. (1922) Effect of Periodic Changes of Angle of Attack on Behavior of Airfoils, NACA Report No. 147, Oct., 1922. (translated from *Zeitschrift für Flugtechnik und Motorluftschiffahrt*, pp. 95-101).
- Knoller, R. (1909) Die Gesetze des Luftwiderstandes, *Flug- und Motortechnik (Wien)*, **Vol. 3, No. 21**, pp. 1-7.
- Koochesfahani, M. M. (1989) Vortical Patterns in the Wake of an Oscillating Airfoil, *AIAA Journal*, **Vol. 27, No. 9**, pp. 1200-1205.
- Küssner, H. G. (1936) Zusammenfassender Bericht über den instationären Auftrieb von Flügeln, *Luftfahrtforsch.*, **Vol. 13, No. 12**.

- Lai, J. C. S. and Platzer, M. F. (1998) The Characteristics of a Plunging Airfoil at Zero Free Stream Velocity, ASME FEDSM98-4946.
- Lai, J. C. S. and Platzer, M. F. (1999) Jet Characteristics of a Plunging Airfoil, *AIAA Journal*, **Vol. 37**, **No. 12**, pp. 1529-1537.
- Lan, C. E. (1979) The Unsteady Quasi-Vortex-Lattice Method with Applications to Animal Propulsion, *Journal of Fluid Mechanics*, **Vol. 93**, **Pt. 4**, pp. 747-765.
- McKinney, W. and DeLaurier, J. (1981) The Wingmill: An Oscillating Wing Windmill, *Journal of Energy*, **Vol. 5**, **No. 2**, pp. 109-115.
- Mehta, U. B. and Zalman, L. (1975) Starting Vortex, Separation Bubbles and Stall: A Numerical Study of Laminar Flow Around an Airfoil, *Journal of Fluid Mechanics*, **Vol. 67**, **Pt. 2**, pp. 227-256.
- Mehta, U. B. (1977) Dynamic Stall of an Oscillating Airfoil, Unsteady Aerodynamics, AGARD CP-227, pp. 23.1-23.32.
- Platzer, M. F., Neace, K. S. and Pang, C. K. (1993) Aerodynamic Analysis of Flapping Wing Propulsion, AIAA Paper No. 93-0484.
- Ramamurti, R., Sandberg, W. and Löhner, R. (1999) Simulations of Flow About Flapping Airfoils Using a Finite Element Incompressible Flow Solver, AIAA Paper No. 99-0652.
- Schmidt, W. (1965) Der Wellpropeller, ein neuer Antrieb fuer Wasser-, Land-, und Luftfahrzeuge, *Z. Flugwiss.* **Vol. 13**, pp. 472-479.
- Smilg, B. (1949) The Instability of Pitching Oscillations of an Airfoil in Subsonic Incompressible Potential Flow, *Journal of the Aeronautical Sciences*, **Vol. 16**, **No. 11**, pp. 691-696.
- Theodorsen, T. (1935) General Theory of Aerodynamic Instability and the Mechanism of Flutter, NACA Report No. 496.
- Tuncer, I. H. and Platzer, M. F. (1996) Thrust Generation due to Airfoil Flapping, *AIAA Journal*, **Vol. 34**, **No. 2**, pp. 324-331.
- Tuncer, I. H., Walz, R. and Platzer, M. F. (1998) A Computational Study of the Dynamic Stall of a Flapping Airfoil, AIAA Paper No. 98-2519.
- Tuncer, I. H. and Platzer, M. F. (2000) Computational Study of Flapping Airfoil Aerodynamics, *Journal of Aircraft*, **Vol. 37**, pp. 514-520.
- Walker, J. M., Helin, H. E. and Strickland, J. H. (1985) An Experimental Investigation of an Airfoil Undergoing Large Amplitude Pitching Motions, *AIAA Journal*, **Vol. 23**, **No. 8**, pp. 1141-1142.
- VanDyken, R. D., Ekaterinaris, J. A., Chandrasekhara, M. S. and Platzer, M. F. (1996) Analysis of Compressible Light Dynamic Stall Flow at Transitional Reynolds Numbers, *AIAA Journal* **Vol. 34**, **No. 7**, pp. 1420-1427.