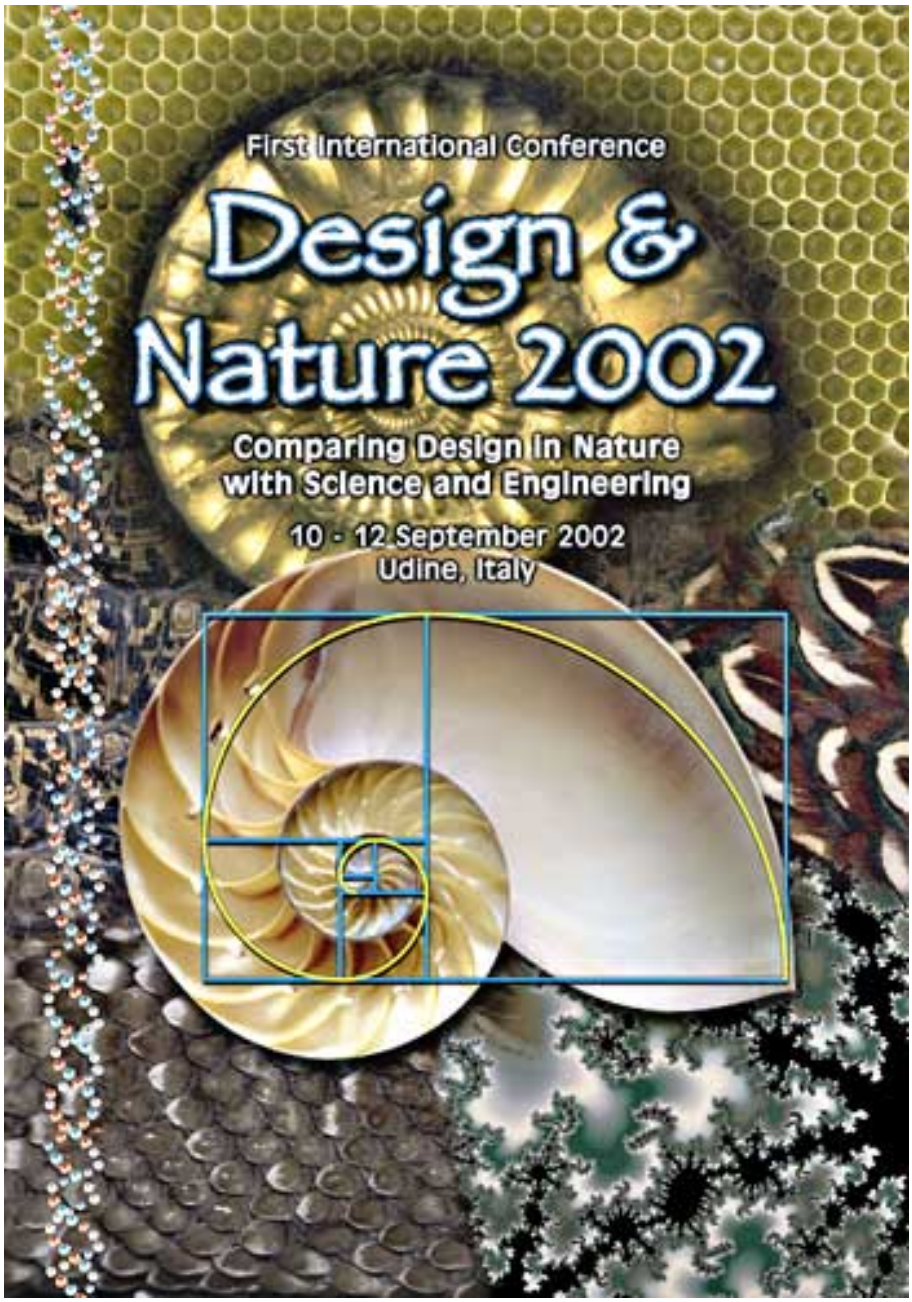
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On the design of efficient micro air vehicles

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Abstract

In the past few years aeronautical engineers have recognized the possibility of building very small air vehicles, so-called *Micro Air Vehicles* (MAVs), in response to specific military and commercial needs. Remotely controlled or autonomous MAVs are difficult to detect because of their small size and low noise emission or, if detected, they may be mistaken for small birds or insects. Yet video cameras and other sensors have become so miniaturized in recent years that it is possible to mount them on MAVs for the purpose of transmitting information which may be difficult to obtain in other ways. In this paper the authors first explain various aspects of the physics of thrust generation due to wing flapping and then review the major computational and experimental results which they achieved during the past few years. They conclude with a description of their MAV which is currently under development.

1 Introduction

Although early flight pioneers, such as O. Lilienthal, were fascinated by the birds' ability to fly by flapping their wings, attempts to build flapping-wing flight vehicles were soon abandoned in favor of fixed-wing or rotary-wing aircraft. On fixed-wing aircraft the thrust and lift generators are clearly separated, whereas on rotary-wing aircraft thrust and lift generation are accomplished by a single system, i.e., the rotor (or rotors) only. It is noteworthy that fixed wing aircraft preceded rotary-wing aircraft by some forty years due to the difficulty of building flight vehicles with integrated propulsion/lift systems.

Birds and insects have mastered the use of integrated propulsion/lift systems for many millenia. It is therefore appropriate to ask whether Nature can provide insights and guidance for the design of flight vehicles which may have new and

practical applications. In this paper, we present a brief overview of our current understanding of the thrust and lift generation mechanisms used by birds and insects. We then describe a micro air vehicle under development at the Naval Postgraduate School which uses the flapping-wing principle, and we conclude by summarizing the connections between the bird/insect flight sciences and the emerging field of micro air vehicle technology.

2 The Physics of Thrust Generation due to Wing Flapping

2.1 Elementary Theory

Knoller [1] and Betz [2] in 1909 and 1912, respectively, were the first ones to propose an explanation of the birds' ability to generate thrust by means of wing flapping. The basic principle is illustrated in Fig. 1, where the airfoil is in the downstroke in the left image and in the upstroke in the right image. The sinusoidal

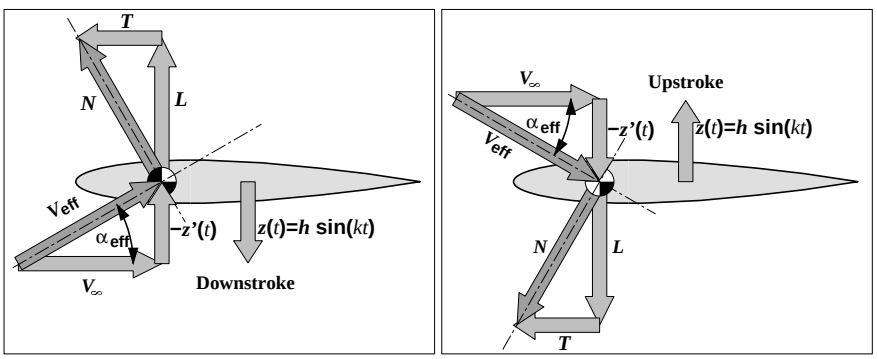

Figure 1: Thrust production during flapping flight

flapping motion, $z(t) = h\sin(kt)$, results in an induced velocity, $-z'(t)$, such that the effective velocity, V_{eff}, is at an angle of attack with respect to the chordline, α_{eff}. According to linear theory, the resultant force vector, N, is normal to the velocity seen by the airfoil, and is therefore canted forward, yielding a net lift, L, and a net thrust, T. During the upstroke the induced velocity changes sign, resulting in a lift force that is downward, but the thrust is still in the direction of flight.

2.2 Two-dimensional Flapping Foil Propeller Theory

The Knoller-Betz elementary theory does not account for the effect of the vortices which are being shed from the trailing edge of an airfoil which executes the sinusoidal plunge motion. It is well known that any change in airfoil incidence angle is accompanied by the shedding of a so-called *starting* vortex. Therefore,

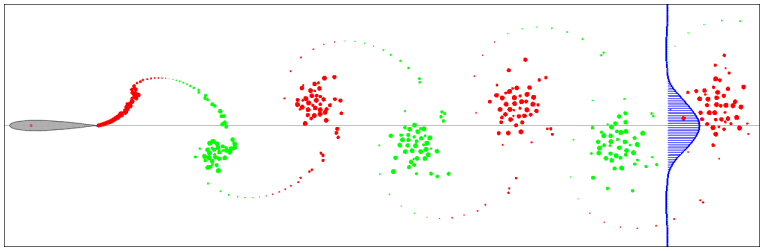

Figure 2: Wake vortices for a sinusoidally plunging airfoil ($k = 3$, $h = 0.2c$).

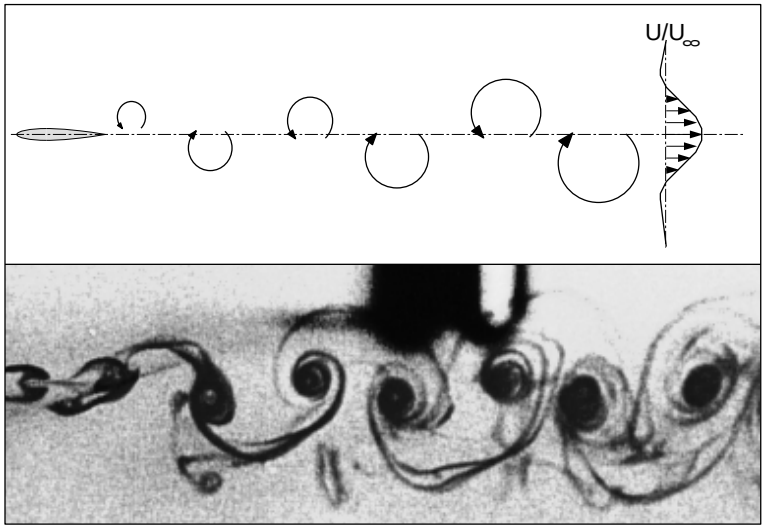

Figure 3: Reverse Kármán vortex street, indicative of thrust ($k = 3$, $h = 0.2c$).

the sinusoidal plunge motion can be regarded as a series of step changes in incidence angle which causes the shedding of vortices. This concept is illustrated in Fig. 2, where an unsteady panel-code solution is shown for an airfoil plunging sinusoidally with an amplitude of 20 percent of the airfoil chord, c, at a reduced frequency of 3 ($k = 2\pi fc/U_\infty$). The largest changes in positive or negative incidence angle occur when the airfoil moves through the top or bottom positions, respectively. Therefore, during one cycle, the airfoil sheds counterclockwise vorticity as it passes through the top position (dark gray), followed by clockwise vorticity as it passes through the bottom position (light gray). As a result, a vortex street is being generated downstream of the airfoil. In Fig. 3, the results of an experimental investigation at the Naval Postgraduate School [3] are shown, where the wake is behind the flapping wing is visualized in a water tunnel by injecting colored dye into the flow. The conditions are the same as that of Fig. 2. It is seen that the counterclockwise vortices are arranged in the upper row, the clockwise vortices in the lower

row, thus inducing a velocity increase between the two rows (shown in Fig. 2). The sinusoidally plunging airfoil therefore acts like a conventional propeller which captures a certain amount of fluid and gives it an increased time-averaged velocity. Laser-Doppler measurements, performed at the Naval Postgraduate School, indeed showed a jet-like time-averaged velocity profile downstream of the trailing edge, confirming that the flapping airfoil can be regarded as a *jet engine* which propels the bird (or flapping-wing vehicle) forward by ejecting a certain amount of fluid in the opposite direction.

2.3 Three-dimensional Flapping Wing Theory

This two-dimensional flow theory is still somewhat incomplete in explaining the actual flow features downstream of a finite-span flapping wing. While no detailed flow visualizations and velocity measurements are available as yet, modern computational techniques already make it possible to obtain a better understanding. In Fig. 4, example calculations are shown for the flow downstream of a sinusoidally plunging finite-span wing, computed using the CMARC code [4]. It is seen that the wing generates a series of vortex rings of alternating sign. A side view of the mid-span flow would yield a vortex street similar to that shown in Fig. 2.

2.4 Effect of Combined Pitch and Plunge Motion

The question naturally arises whether it is better to flap a wing in pure plunge or pitch motion or to use a combined pitch and plunge motion. Again, these questions can be readily answered by performing modern panel code calculations. Sample results from a two-dimensional panel code, developed at the Naval Postgraduate School, are compared to Garrick's linear theory [5] in Fig. 5, for a NACA 0012 airfoil pitching about its quarter chord with a pitch amplitude of 4 degrees, a plunge

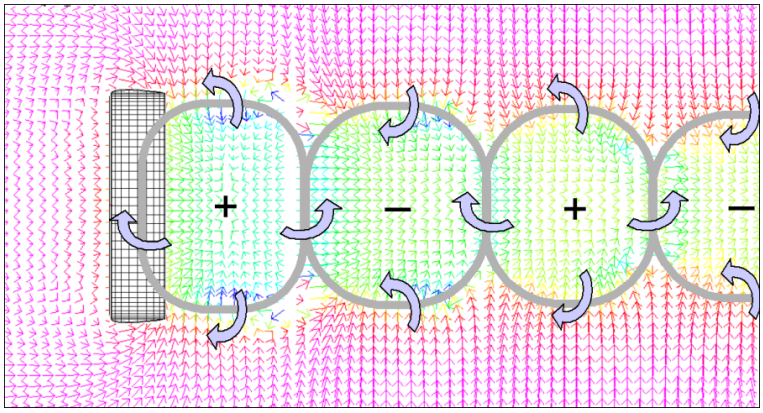

Figure 4: Perturbation velocity vectors illustrating the cyclic vortex rings.

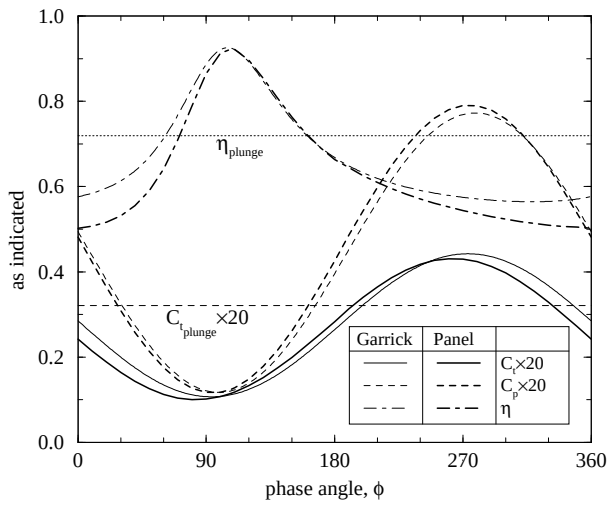

Figure 5: Predicted thrust & efficiency.

amplitude of $0.2c$, and a reduced frequency of 0.5 [6]. The predicted thrust and power coefficients as well as their ratio (the propulsive efficiency, η) are shown as a function of the phase angle between pitch and plunge, ϕ. The two horizontal lines indicate the thrust and efficiency of a purely plunging airfoil. A combined pitch/plunge oscillation is clearly more efficient than a pure plunge oscillation, provided the pitch oscillation leads the plunge oscillation with a phase angle of about 90 degrees. A pure plunge oscillation produces a higher thrust than a combined pitch/plunge oscillation, but at a lower efficiency. Furthermore, thrust can be increased by either increasing the flapping amplitude or the frequency. However, it is always more efficient to increase the amplitude rather than the frequency, provided the flow remains attached to the airfoil. In effect, it is more efficient to impart a small velocity surplus over a wide region than a high velocity surplus over a narrow region. A pure pitch oscillation (not shown) will produce thrust only if the airfoil oscillates at rather high frequencies, and the efficiency will be quite low.

2.5 Ground Effect

Pilots are well aware of the favorable ground interference effect at take-off or landing which increases the wing lift and reduces the so-called induced or vortex drag. A similar effect occurs for a flapping wing flying in close proximity to the ground. The effect can be simulated computationally by adding a second airfoil which flaps in counterphase as shown in Fig. 6, where the symmetry-plane between the two wings represents the ground-plane. Panel code calculations predicted that the thrust would increase, and this was confirmed experimentally, as shown in Fig. 7 [6]. In this case the airfoils plunge with an amplitude of $0.4c$ and a mean height

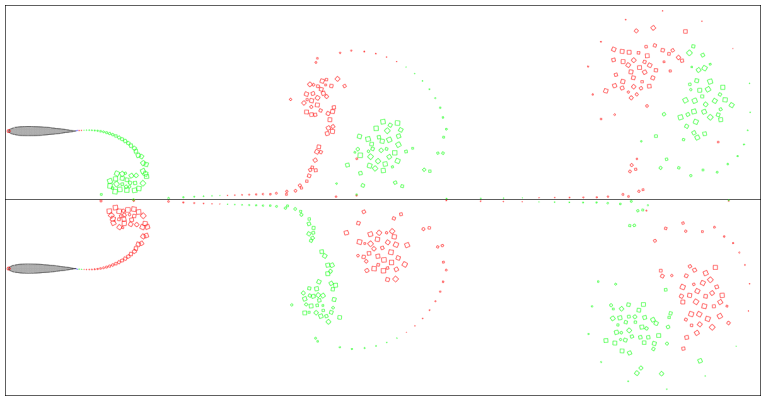

Figure 6: Wake of a wing flapping in ground effect.

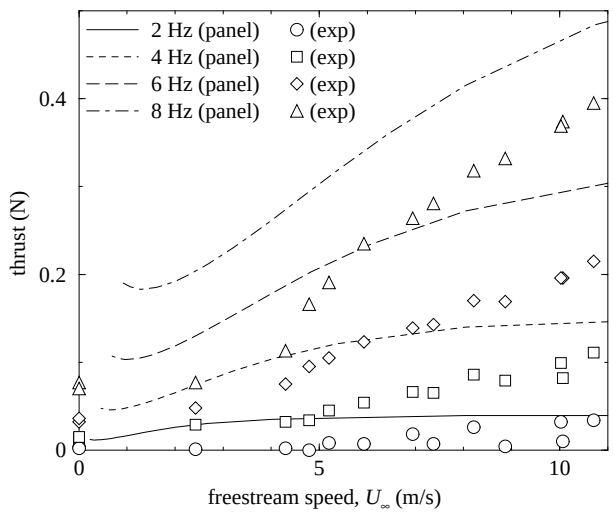

Figure 7: Thrust for a wing flapping in ground effect.

above the ground plane of $0.7c$.

2.6 Dynamic Lift/Stall Effect

Helicopter pilots know that the flow can become separated from the helicopter blade leading edge thereby causing dynamic stall. This effect occurs because the blade is oscillating. The basic physics is illustrated in Fig. 8 where a sequence (top-to-bottom left column, then top-to-bottom right column) of images during the downstroke is shown from a Navier Stokes simulation of a NACA 0014 airfoil that is sinusoidally plunged at a reduced frequency of 1, with an amplitude $0.4c$, and

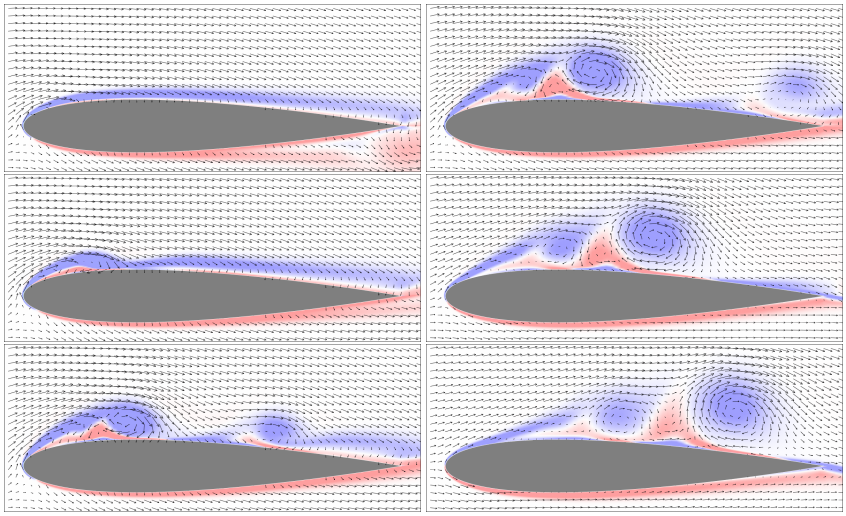

Figure 8: Dynamic stall on a plunging airfoil.

at a Reynolds number of 10^4. Note, the Reynolds number is a non-dimensional parameter that is loosely defined as the ratio of inertial to viscous forces acting on a wing. Commercial jets fly at Reynolds numbers on the order of 10^7, whereas birds fly at Reynolds numbers on the order 10^4, and insects fly at Reynolds numbers on the order of 10^2. A strong so-called dynamic stall vortex forms near the leading edge which propagates over the upper surface and is then swept downstream past the trailing edge. While the vortex is over the airfoil upper surface lift is generated which is significantly greater than the static lift which would be generated at the corresponding static incidence angle. As soon as the vortex approaches the trailing edge this lift is reduced quite suddenly and dramatically. While the presence of dynamic stall is generally adverse on aircraft, there is evidence that birds and insects may benefit from this effect. Indeed, we have made measurements and computations which show that dynamic stall occurs on the micro air vehicle described in the next section.

3 Flapping-Wing Micro-Air Vehicle

The preceding computational and experimental studies led us to the micro air vehicle configuration shown in Fig. 9. The 15 cm square model uses two small wings at the back, arranged in a biplane fashion, to provide the propulsion, and the remainder of the vehicle is essentially a large wing, providing most of the lift and all of the internal volume. The two aft wings flap in counterphase, with an amplitude that is constant in the spanwise direction. The biplane arrangement provides the performance benefits of flight in ground effect without having to be near the ground. Additionally, the system is aerodynamically and mechanically balanced such that

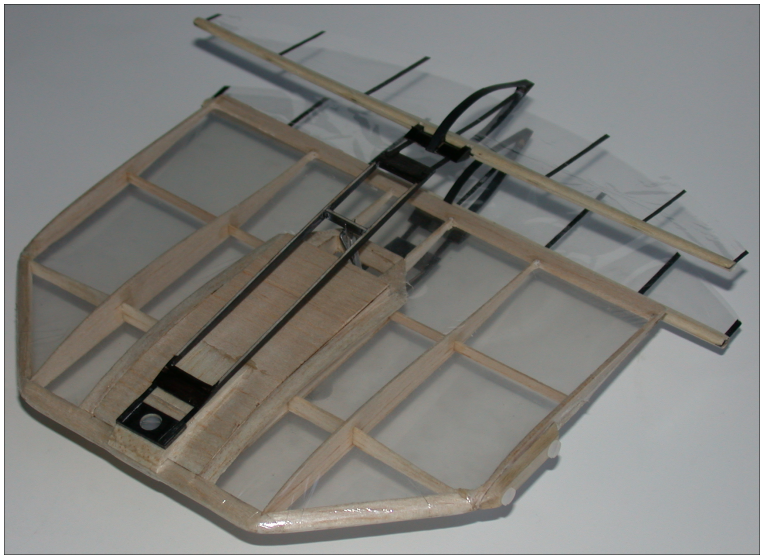

Figure 9: 15 cm flapping-wing MAV model.

the body of the aircraft does not oscillate with the flapping, and therefore no work is expended on periodic accelerations of non-lifting mass.

The wings are only driven in plunge, but they are elastically mounted such that they aeroelastically pitch, yielding tunable, but mechanically simple pitch/plunge motions. Similarly, the wing camber is elastic, and is aeroelastically coupled to the motion, yielding significant improvements in thrust.

Early test models included only the aft flapping wings and a slender fuselage, and were driven using a 5 mm geared stepping motor. Flapping frequencies as high as 40 Hz were achieved, but elastic deformations of the structure led to performance losses at frequencies above about 25 Hz. Preliminary experimental thrust measurements indicated significant losses in thrust with increasing speed, a strong indication of adverse dynamic stall effects, as shown in Fig. 10 [7]. In recent static tests of improved models, thrusts as high as 14 grams have been achieved, and a model was developed that could take off vertically and hover while under tether. It is hoped that improvements in the design as well as proper tuning of the elastic pitch and camber deformations will result in beneficial effects from dynamic stall, in the same way that most insects do. The model shown is driven by a small DC brushed motor, like those used to vibrate pagers, powered by a single NiCad 50mAh rechargeable battery and a DC-DC converter. It has a total weight of about 12 grams. Current work is directed toward achieving sufficient lift and control for remotely controlled flight.

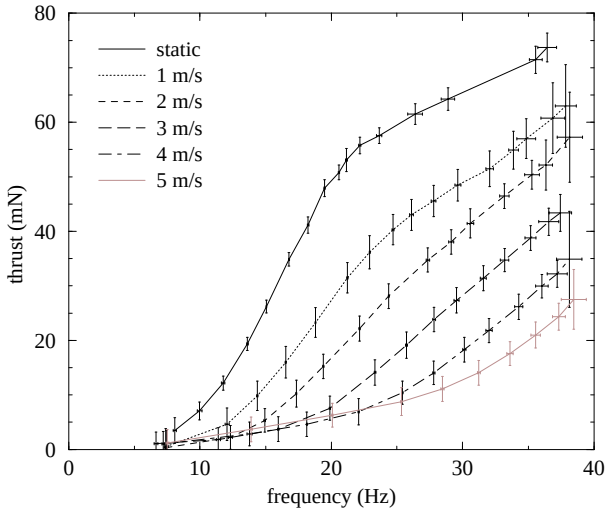

Figure 10: Thrust measurements for the rigid-wing MAV.

4 Considerations on the Design of Micro-Air Vehicles

The design of micro air vehicles presents the aeronautical engineer with the challenge of understanding and optimizing flight at very low Reynolds numbers. It is too early to say whether the propulsion system which has no analog in nature, namely the conventional propeller, will remain the better choice at the micro air vehicle scale. Nature evolved various flapping wing systems for fully integrated thrust and lift generation. This indicates the desirability, and perhaps even necessity, to provide the micro air vehicle designer with the same wealth of aerodynamic data aeronautical engineers use for the design of high Reynolds number vehicles, i.e., airplanes. Our studies indicate that computational data which are based on the assumption of purely inviscid attached flow are of only limited value for the design of micro air vehicles. This is clearly seen in Fig. 11, where high and low Reynolds number results are compared to experimental results. Birds and insects appear to make very effective use of the dynamic stall phenomenon briefly described above. Indeed, some birds and insects seem to exploit the interaction between dynamic stall vortices shed from two closely spaced wings. These are phenomena which are as yet poorly understood, difficult to compute and unrealizable on an experimental model. Hence, there is still very much to be learned from Nature for the design of micro air vehicles.

5 Acknowledgements

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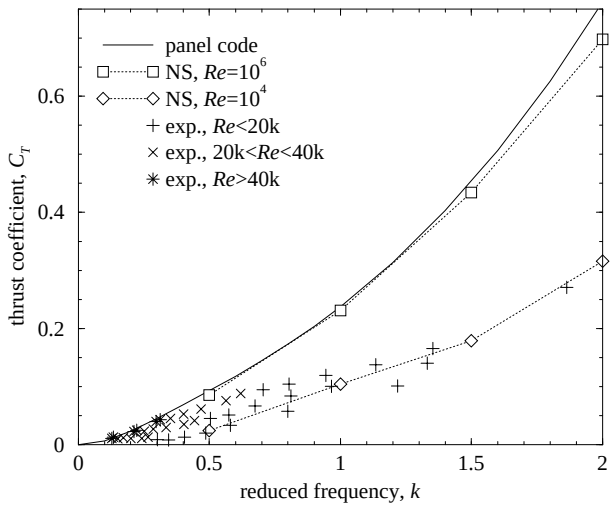

Figure 11: Reynolds number trends in performance.

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