

# Flapping-wing aerohydromechanics in nature and engineering

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## Abstract

Flapping wings have been the propulsion system used by birds, insects and fish for millions of years. Yet, the preferred system for aircraft and ship propulsion is the propeller or jet engine. It is the objective of this paper to show that recent interest in the development of micro air vehicles may lead to the adoption of flapping-wing propulsors as the superior system. Also, it is shown that flapping hydrofoils may have potential as effective water energy conversion devices. The knowledge gained in the aerohydromechanics of birds, insects and fish therefore may soon be applied to the design of air vehicles and power generators.

*Keywords: air vehicle design, hydropower generation, flapping-wing aerohydromechanics.*

## 1 Introduction

Birds, insects, fish and cetaceans use flapping wings as thrust and lift generators. Therefore, it is not surprising that the idea of adopting flapping wings for the propulsion of man-made objects was examined as early as 1490 by Leonardo da Vinci. At the end of the 19<sup>th</sup> century and the beginning of the 20<sup>th</sup> century, numerous attempts were made to develop flight vehicles using flapping wings. One of these early flight pioneers was Otto Lilienthal in Berlin, who remarked about his fascination in observing the flight performance of storks [1]. Indeed, anyone looking at fig. 1 will marvel at the pelican's flight abilities. An examination of the scientific literature on the aerohydromechanics of flapping wings, as conducted recently by Rozhdestvensky and Ryzhov [2], reveals many studies of the physics of flapping-wing propulsion with the goal of exploring



their potential as efficient propulsors and lift generators as well as wind and water energy conversion devices.



Figure 1: A brown pelican takes advantage of ground effect on Monterey Bay.

As stated by Rozhdestvensky and Ryzhov, interest in flapping-wing devices is justified because propulsive systems with flapping wings can be viewed as “ecologically” pure, are relatively low-frequency systems, possess sufficiently high efficiency, are multi-functional in the sense of being capable of operating in different regimes of motion, can combine the function of propulsor, control device, and stabilizer, can provide static thrust, can provide high maneuverability, possess more acceptable cavitation characteristics than conventional propellers, have relatively low aerodynamic drag in the “switched-off” position, and allow the use of modern controls, MEMS, piezo-electric, reciprocating chemical muscles, and other technologies.

Furthermore, the phenomenon of wing flutter is well known to aeronautical engineers causing an aircraft wing to absorb energy from the air flow due to the self-excited wing vibration. Flapping wings therefore have the potential of serving as efficient wind or hydropower generators.

Yet, it is a fact that flapping wings have found few applications as airplane or ship propulsors and as power generators. This raises the question whether systems which have been favored by nature for millions of years are inherently less suitable for man-made applications or whether this situation is likely to change in the near future because of the need for new vehicles and energy conversion devices. It is the objective of this paper to address this question.

## 2 Fundamentals of thrust generation by wing flapping

Airplanes are being propelled by ejecting high-velocity air from the propeller or the jet engine. It may not be obvious that the same principle holds for flapping wings. This can be understood from fig. 2. In a). we show a visualization of the

flow generated downstream of a NACA 0012 airfoil in a low-speed water flow. The foil is held steady at zero angle of attack. It is seen that a so-called vortex street is shed from the trailing edge consisting of two rows of vortices. The upper-row of vortices are turning clockwise, the lower-row of vortices are turning counter-clockwise. This type of vortex street is usually referred to as a Kármán vortex street, named after Theodore von Kármán who first explained its structure. The following three visualizations show the vortex streets which are being generated when the airfoil starts to flap in the vertical direction (pure plunge mode) with increasing frequency. It is seen that the vortex street eventually becomes the exact reverse of the Kármán vortex street shed from the stationary airfoil. It is therefore often referred to as the reverse Kármán vortex street. A closer inspection of the velocities induced by this vortex street reveals that counter-rotating upper-row vortices together with the clockwise lower-row vortices induce a time-averaged flow between the two rows which has the shape of a jet. Hence wing flapping achieves the same effect as man-made propellers or jet engines.

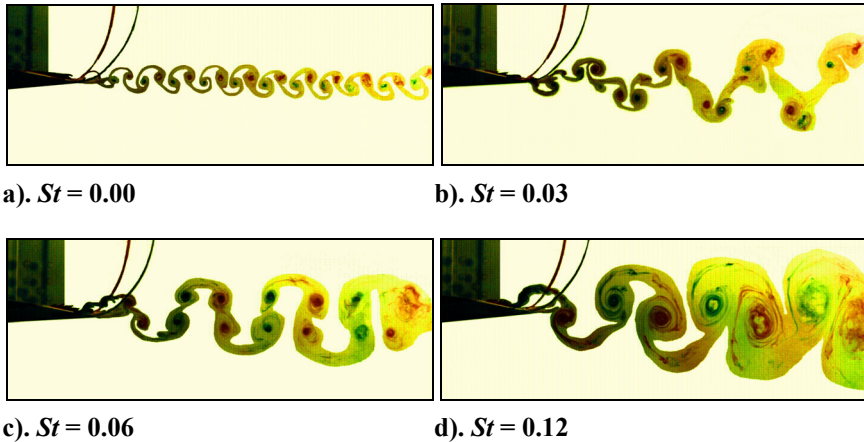


Figure 2: Vortex street formation with increasing Strouhal number.

A still closer inspection leads to the recognition that there are three parameters which affect this process, namely the amplitude and frequency of oscillation and the flying speed of the bird, insect, fish or cetacean. The flow features remain similar when the product of frequency,  $f$ , and amplitude,  $A$ , divided by the flying speed,  $U$ , remains constant. This quantity is usually denoted as the Strouhal number given by

$$St = fA/U. \quad (1)$$

The frequency and amplitude must be sufficiently large in order to generate a reverse Kármán vortex street and therefore a significant amount of thrust, as

shown in fig. 2. Most importantly, the flying speed must be small in order to obtain a sufficiently large Strouhal number which will lead to thrust generation.

This insight leads to the conclusion that flapping wing propulsion is inherently limited to relatively low-speed flight or low-speed motion in water. Hence, flapping-wing powered man-made vehicles are likely to be low-speed vehicles. It is therefore not surprising that flapping-wing systems received relatively little attention in the last century because speed was always a major objective.

### 3 Flapping-wing powered micro air vehicles

However, it now appears that a new class of vehicles is becoming of interest for a number of applications. It is the class of micro air vehicles (MAV) or nano air vehicles (NAV). MAVs are defined as vehicles whose length, span or height does not exceed 15 cm. NAVs have dimensions not exceeding 7.5 cm. Clearly, such vehicles have sizes comparable to those of birds, fish and, ultimately, of insects. The aeronautical and hydronautical engineer therefore is faced with the question of whether propulsion and lifting systems developed by nature are better suited for typical MAV and NAV missions than the conventional rotary systems developed over the past century.

It is too early to give a definitive answer to this question and we merely refer to our recent review paper [3] on this subject and the additional references quoted therein. Instead, we draw attention to two flapping-wing powered unmanned air vehicles which have been developed in recent years.

Basically, two approaches might be used for the development of flapping-wing powered vehicles. One may want to imitate existing living creatures to the maximum possible extent. This approach is usually referred to as the biomimetic design approach. The second method is based on the adoption of only a few features found in nature while retaining other features from conventional man-made vehicles. This is the biomorphic design approach.

The AeroVironment Company in California chose to pursue the biomimetic approach by imitating conventional bird flight. This vehicle called the *Microbat* is shown in fig. 3. It evolved from the well known rubberband powered designs by substituting an electric motor drive-train for the rubberband and adding a radio for control. The energy for the motor is supplied by a Lithium-polymer (LI-poly) battery. The span is 23 cm and the total vehicle weight is 14 g. It has made flights of 25 minutes duration.

In contrast, we have chosen the biomorphic design approach for our vehicle shown in fig. 4. It has a fixed wing for lift generation and two wings mounted behind the fixed wing which flap in counterphase, i.e., when the upper wing moves up the lower one moves down and vice versa. In this way the joint center of gravity of the two flapping wings remains stationary and therefore the flapping oscillation does not cause undesirable oscillation of the complete vehicle.

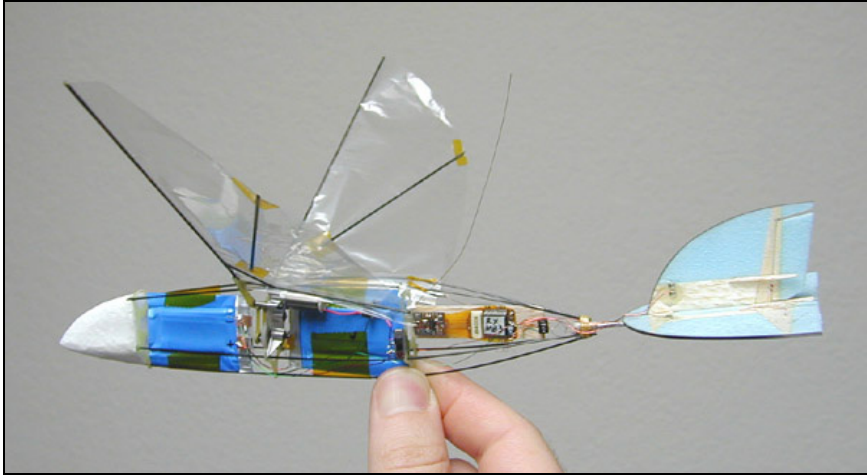


Figure 3: AeroVironment Microbat.

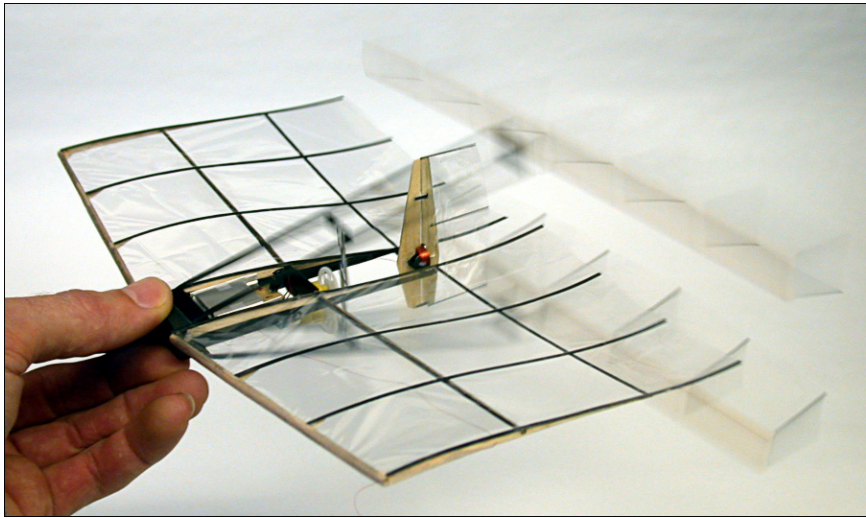


Figure 4: Authors' biomorphic flapping-wing propelled MAV.

Furthermore, the two flapping wings flap with constant amplitude along the span. This has the advantage that thrust is generated along the whole span in contrast to the bird wing where the flapping amplitude and hence the thrust decrease to zero at the wing root. Clearly, the bird has no choice whereas we were free to adopt only those features from nature which were most useful for our purpose. In this case we adopted from nature only the flapping wing concept, but retained the conventional airplane design feature of separating the thrust and lift generators. Actually, our arrangement is somewhat more sophisticated than

that because the flapping wings are mounted very close to the trailing edge of the stationary wing and therefore the three wings influence each other. It turns out that this mutual interaction is quite beneficial because the flapping wings cause an upstream entrainment effect which keeps the flow over the upper surface of the fixed wing attached to much larger incidence angles than would otherwise be the case. Our MAV therefore is remarkably insensitive to wind gusts.

Another interesting question is raised by our use of flapping wings in a biplane arrangement. We adopted this concept because our computational and experimental studies showed that flapping biplane wings generate more thrust and have higher propulsive efficiency than single wings. The effect is equivalent to flight of a single wing near a planar surface, such as the ocean surface. It is referred to as the ground effect. The pelican shown in fig. 1 flies in ground effect. One may therefore wonder whether flapping biplane wings evolved in nature. Although there are no current insects or birds using the biplane concept the answer, surprisingly, is that there is evidence of insects using this concept many millions of years ago. As discussed by Wootton and Kukalova-Peck [4], homiopteridae are an ancient group of large, sometimes gigantic insects, found in Carboniferous insect beds. Most had unusually large wings. The hind wings were usually broader-based than the fore-wings, but they overlapped extensively. This extensive overlapping appears to have been the case also for some members of the family Lycocercidae. In fact, in one case the wings appear to have overlapped almost completely. It remains an interesting question why biplane insects became extinct. Birds, on the other hand, evolved from 4-limbed ancestors, and since other requirements for survival required two to remain as legs, it was essentially impossible for birds to evolve into the biplane arrangement that we use, and yet, the Pelican in fig. 1 is most of the way there. He gets all the benefits of ground effect, but still misses out on the benefits of mechanical balance.

More details about this design, development and flight performance can be found in references [5] and [6].

## 4 Flapping-wing power extraction

The possibility of energy extraction from an air stream due to wing vibrations is a well known phenomenon in aeronautical engineering. Wing flutter can be so dangerous that it may break a wing in just a few seconds. The fundamental underlying mechanism can be understood by looking at fig. 5 which shows an airfoil that can oscillate in a combined pitch and plunge motion. It is readily seen from the upper figure that the lift acts in the same direction as the airfoil's motion if the pitch motion leads the plunge motion by 90 degrees. This implies that a net amount of work is done by the air on the airfoil, i.e., a certain amount of energy is absorbed from the air by the airfoil. As a result the amplitude of the airfoil oscillation will increase until the wing breaks. On the other hand, in the lower figure, the phase angle between the motions is zero and the lift opposes the motion during parts of the airfoil oscillation cycle. Hence in this case no net work is done by the air on the airfoil and no energy is transferred to the airfoil.



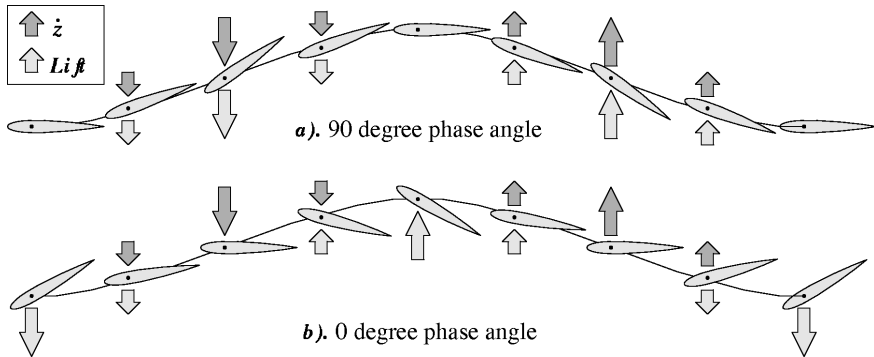


Figure 5: Combined pitch/plunge airfoil oscillation with a) 90 degree phase b) 0 degree phase angle.

It is evident that this phenomenon can be used for power generation if the airfoil motion is linked to an electric generator. McKinney and DeLaurier [7] built such an oscillating-wing power generator already a quarter of a century ago and showed the feasibility of extracting energy from a wind stream. However, little work was done since then to explore the competitiveness of such a system with the conventional wind turbines using rotating blades.

However, in recent years this possibility of power generation attracted interest in Great Britain, Germany and the United States for the extraction of the kinetic energy available in rivers and tidal streams. For example, according to J. Blumenfeld, director of San Francisco's Environment Department, nearly 400 billion gallons of water rush each day through the San Francisco Golden Gate at a speed of about 4 knots. If harnessed, the energy from this water could be an answer to the city's power needs [8].

Similar considerations motivated the British company *Engineering Business Limited* [9] to propose a tidal stream generator based on the flapping wing concept. Serious development of the technology started in late summer 2001 with the support of the British Department of Trade and Industry under its New and Renewable Energy Program. This generator consists of a large hydroplane which has a chord length of 3 m and a span of 15.5 m. Its angle of attack is varied to produce lift and drag, which forces a support arm to oscillate up and down. The arm is restrained by hydraulic cylinders and the resulting high pressure oil is used to drive a hydraulic motor, close-coupled to an electric generator. The design power output was 150 kW during operation in a 4 knot current. During the following three years this generator was built and mounted on the seabed of Yell Sound in the Shetland Islands. The company was able to demonstrate satisfactory operation, but the further development of the system was halted due to lack of follow-on funding.

In Germany a small company *Aniprop GmbH* [10] developed a small flapping-wing hydropower generator which was installed in summer 2003 in a channel located in the city of Augsburg. The generator consists of a single



hydrofoil with a chord length of 0.4 m and a span of 1.9 m. The power output was approximately 3 kW in a water flow of 2 m/s. Testing and further development of this generator is still continuing.

In the United States we started in 1996 with development of a micro hydropower generator which had a single hydrofoil of 62 mm chord length and a span of 350 mm. We then improved this generator by employing two wings in the tandem arrangement shown in fig. 6. The two hydrofoils were forced to flap with a 90 degree phase difference, such that the null spot of one coincided with the power stroke of the other. The hydrofoils could be forced to plunge with amplitudes up to  $1.4c$  and pitch amplitudes up to 90 degrees. This generator was tested in a water tunnel at water velocities up to 0.4 m/s. Further details can be found in reference [11]. Encouraged by this experience, we have developed a new generator with an expected power output of several kW. Tests of this new generator are currently underway.

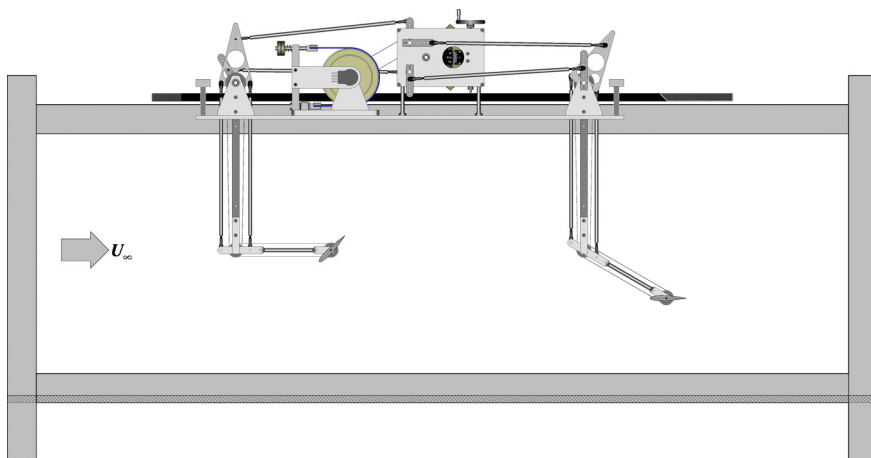


Figure 6: Authors' twin-wing hydropower generator in the water tunnel.

## 5 Summary and outlook

Aeronautical and power engineering are typically associated with systems not found in Nature, i.e., with propellers, jet engines, turbines etc. In this paper we tried to show that the design of new air vehicles, especially micro air vehicles, can benefit from propulsion and lift generation systems evolved by Nature over millions of years. Rubber powered birds could be purchased in many toy stores and such "micro air vehicles" were indeed regarded as toys of no practical value. Yet, it is now becoming clear that the coalescence of three technologies, namely flapping wing technology combined with enormous progress in battery and miniature electronics technologies, is soon making it possible to develop air



vehicles with great potential utility for a number of flight missions. Similarly, flapping hydrofoils are likely to open up new possibilities for renewable energy generation. Hence, it appears that there is much to be learned from Nature to stimulate new developments in aeronautical and power engineering.

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