FLAPPING-WING TECHNOLOGY: THE POTENTIAL FOR AIR VEHICLE PROPULSION AND AIRBORNE POWER GENERATION

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Abstract

Birds, insects, fish, and cetaceans have evolved and used flapping-wing systems for thrust and lift production for years. Flapping wing propulsion is considered to be much more efficient and manoeuvrable at the scale of Micro Aerial Vehicles (MAV) and has recently become a subject of intensive research. The potential of applying flapping wing technology developed for a MAV configuration to High-Altitude Long-Endurance (HALE) Vehicle is highlighted. Simple estimates, supported by preliminary Navier-Stokes calculations indicate the feasibility and potential superiority of flapping-wing airborne power generators over previously proposed rotary power generators.

1 Introduction

Biological systems offer many examples of performance that far outstrips what can currently be achieved artificially; the flight of insects and birds is a prime example for small-scale flying vehicles, as well as being a topic of fascination to observers of the natural world from Pliny through Leonardo DaVinci to David Attenborough. The objectives of this paper are to draw attention to the potential of flapping-wing technology for the development of non-conventional air vehicles (especially for low Reynolds number flight applications), and to propose the new concept of using flying flapping-wing power generators for the purpose of tapping into the abundant energy available in the global jet streams. The current status of oscillating-wing power generation technology is reviewed. The feasibility of an airborne flapping wing power generator is examined by conducting preliminary design estimates supported by Navier-Stokes calculations. The concept of using multiple HALE vehicles with flapping-wing power generators to extract energy from the global jet streams is discussed.

2 Flapping-Wing Micro Air Vehicle

Fig. 1 shows the flapping-wing micro air vehicle (MAV) that was developed by Platzer and his associates [1]. It consists of a fixed wing (with dihedral for good roll stability) and two flapping wings which are elastically mounted on two swing arms. The two swing arms are driven by a crankshaft so that the two wings are flapping in counterphase. This arrangement has the advantage of keeping the joint center of gravity constant, thus eliminating undesirable vehicle oscillation.

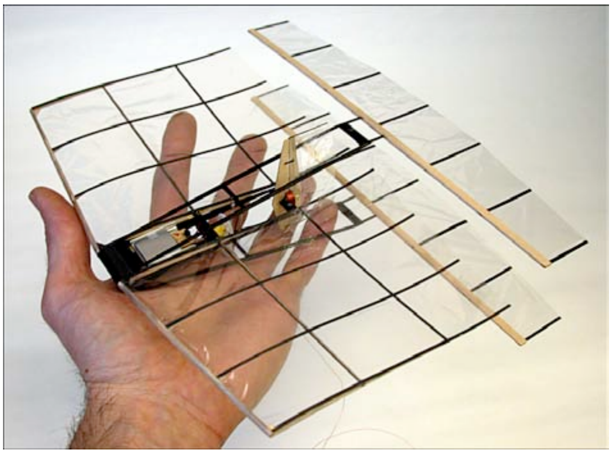

Fig. 1. Flapping-Wing Micro Air Vehicle [1].

It has the further advantage of increasing the thrust and propulsive efficiency compared to a single flapping wing of equal wing area. The aerodynamics of two wings flapping in counterphase is equivalent to that of a single wing flapping near the ground. The benefits accruing from this ground effect were ascertained both computationally and experimentally and are described in some detail in references [2] and [3]. Relatively high aspect ratio flapping wings were selected to obtain superior cruise performance and the flapping amplitude was intentionally kept constant along the span in order to maximize the achievable thrust. Furthermore, a closely coupled fixed and flapping-wing combination was chosen so that the flapping wings, mounted downstream but near the trailing edge of the fixed wing, entrain the boundary layer of the fixed wing. Wind tunnel tests of this configuration verified that wing stall is delayed to relatively high incidence angles, thus making it possible to vary the lift coefficient, and therefore the flight speed, over a wide range. As a result, the flapping-wing MAV, shown in Fig. 1, has the dual-mission capability of cruising at 5 m/s and loitering at 2 m/s. It has a span of 25 cm, weighs less than 14 gram, and can fly more than 15 minutes on a single rechargeable Lithium-polymer cell.

It is important to choose flapping frequency and amplitude values that yield optimum performance. Several studies of flapping-wing and tail propulsion in nature have shown that most animals cruise within a narrow band of the Strouhal number *Sr*, defined as:

$$Sr = f A / U \tag{1}$$

where f is the flapping frequency, A is the flapping amplitude (taken as the total excursion of the tail trailing edge), and U is the flight speed. This narrow band lies in the range $0.2 < Sr < 0.4$.

The most recent studies of the mechanisms influencing the efficiency of oscillating airfoil propulsion are those of Young and Lai [5]. Their Navier-Stokes calculations for a NACA 0012 airfoil undergoing pitching and plunging motions in the Reynolds number range Re = 20,000 - 40,000 confirmed that an efficiency peak naturally emerges somewhere in the range of $0.1 < Sr < 0.4$ because viscous forces start to dominate at low Strouhal numbers and therefore reduce the efficiency. On the other hand, once the optimum Strouhal number is exceeded too much vortical energy is being shed into the wake that is not being converted into thrust. However, Young and Lai [5] also showed that the Strouhal number alone is insufficient to characterize the efficiency of flapping-foil propulsion, especially when significant leading or trailing edge separation occurs.

The MAV shown in Fig. 1 operated at the following conditions: flapping frequencies up to 40 Hz, flapping amplitudes up to a chord-length, and flight speeds between 2 to 5 m/s. This corresponds to Strouhal numbers between 0.16 to 0.8 and Reynolds numbers (based on the chord length of the fixed wing) between 20,000 to 50,000. Hence it is seen that the MAV shown in Fig. 1 operates in the optimal Strouhal number range.

The flow entrainment effect provided by the flapping wings has the further advantage of giving the MAV a remarkable gust insensitivity. Flight tests verified that the vehicle remains controllable up to angles of attack of approximately 20 degrees, indicating the absence of massive wing stall of the fixed wing in this angle of attack range. This fact was also verified by wind tunnel tests. Flow visualizations are shown in Fig. 2. In the upper image the biplane wings are stationary and the flow separates from the leading edge of the fixed wing. In the lower image the biplane wings are flapping in counterphase and the flow is seen to reattach to the wing upper surface.

3 Flapping-Wing High-Altitude Long-Endurance Vehicle

Very recently, there has been increased interest in the development of high-altitude long-endurance (HALE) aircraft. The British company QinetiQ developed a HALE unmanned air vehicle “Zephyr” which is currently being flight tested. Zephyr is an ultra-lightweight carbon-fiber aircraft weighing around 30 kg, powered by lithium-sulphur batteries that are recharged during the day using solar power. It is propelled by two tractor propellers mounted in front of an 18m-span wing. Zephyr achieved a 54-hour flight, reaching an altitude of 58,355 feet in August 2007. The United States Defense Advanced Research Projects Agency (DARPA) has awarded contracts to the Aurora, Lockheed and

Boeing companies to develop a high-altitude long-loiter (HALL) aircraft "Odysseus" which is designed to fly in the stratosphere for up to five years. It is a much larger aircraft with a wing span of 164 feet, has nine tractor-propellers and a payload capability of 1000 pounds. As Zephyr, Odysseus flies at night on energy from on-board batteries.

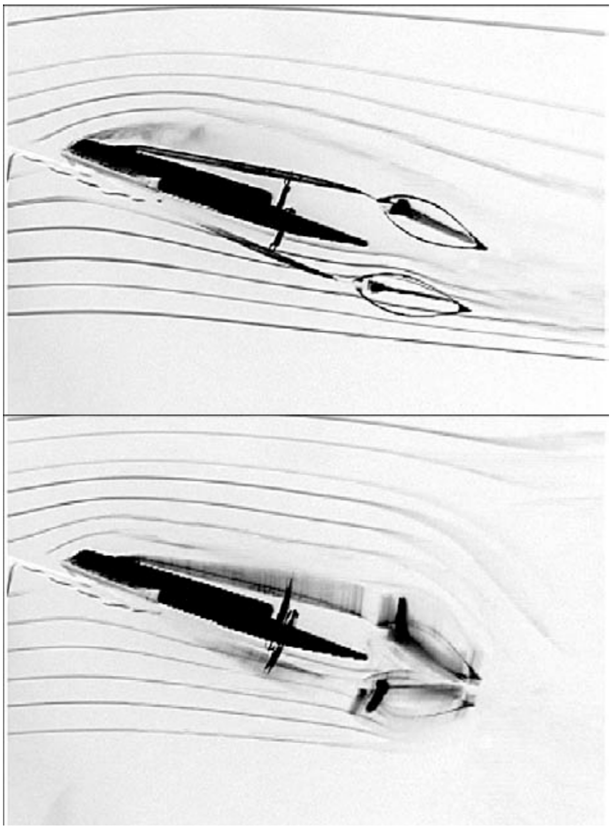

Fig. 2. Flow visualization of separation control on the fixed/flapping-wing model [1].

High-altitude long-endurance (HALE) vehicles are prone to be quite sensitive to flow separation effects because of the low flight Reynolds numbers encountered by these vehicles. For example, assuming a wing chord of 1 m for the Zephyr wing, the wing Reynolds number at an altitude of 20 km is only 142,000. Therefore, the question arises whether flapping wings instead of propellers might offer advantages for HALE aircraft. This possibility seems to have been first explored at ONERA by Pendaries et al [6].

We propose that the flapping-wing configuration shown in Fig. 1 is likely to offer significant advantages for HALE aircraft. As first explained by Betz [7], an aircraft's propulsive efficiency is improved when the air from the wing wakes is used as part of the propulsive stream so that with wake ingestion the power expended can actually be less than the product of the forward speed and aircraft drag. For this reason A.M.O. Smith [8] proposed to use the boundary layer air for propulsion. Leroy Smith [9] of the General Electric Company quantified the potential benefits of wake ingestion as recently as 1993. The configuration shown in Fig. 1 makes it possible to exploit this effect. Any HALE vehicle will, of course, have a higher aspect-ratio fixed wing than the MAV in order to increase the flight efficiency. Consequently, the flapping wings will also have a higher aspect ratio. Assuming dimensions similar to the Zephyr wing, 1 m chord and 18 m span, the flapping-wing HALE aircraft will fly at around 17.5 m/s to develop enough lift to balance the weight of 30 kg at a lift coefficient of 1.0 at an altitude of 20 km. Assuming a drag coefficient of 0.06, the total drag is estimated at 18 N which can be overcome by using two biplane flapping-wing propellers, as shown in Fig. 1, with a span each of 5 m and a chord of 0.25 m, flapping at a frequency of approximately 10 Hz. This estimate is based on the Navier-Stokes analyses of Young and Lai [5] for single flapping wings and of Kaya et al [10] for biplane propulsors. Further computational and wind tunnel studies are required to improve this estimate and to determine the optimum compromise between the aerodynamic and structural design constraints. These refinements are currently in progress and will be presented in the near future. However, there is now sufficient design and flight test information available from the flapping-wing MAV development to propose this configuration as an attractive HALE candidate. The advantages to be obtained from this configuration are the improved propulsive efficiency due to wake ingestion and the stall insensitivity over a large lift coefficient range (and hence flight speed range) due to the powerful flow control mechanism enabled by the close-coupled wing/flapping propeller arrangement.

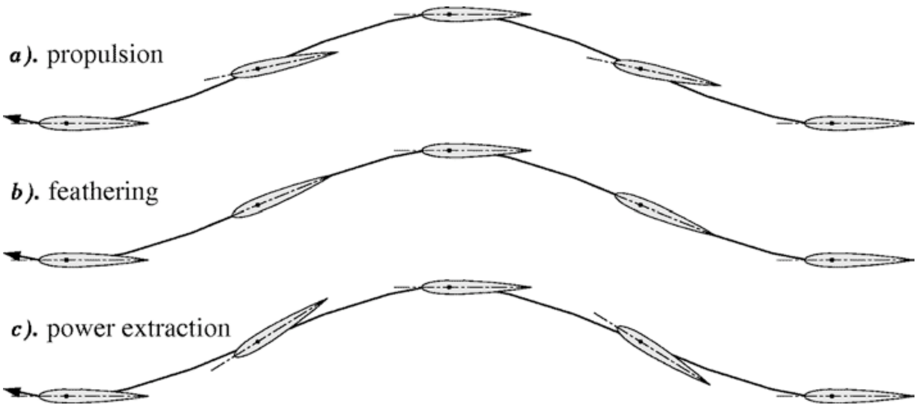

Fig. 3. Airfoil in combined pitching and plunging flight.

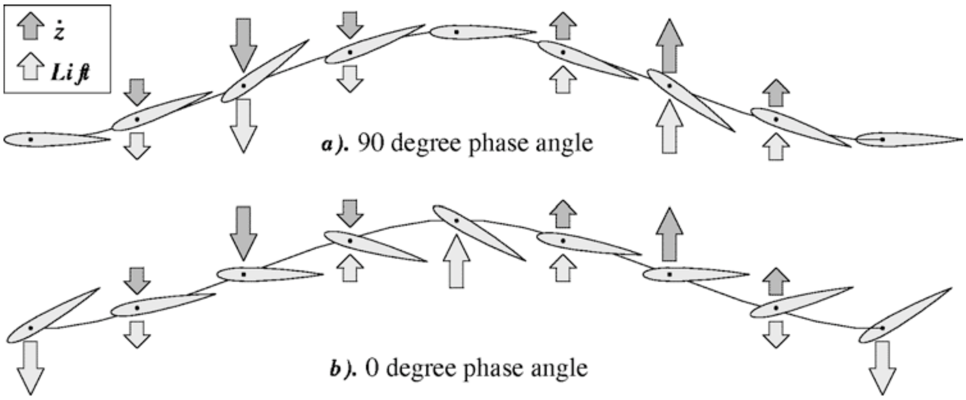

Fig. 4. The flutter phenomenon.

4 Flapping-Wing Power Generation

The rapidly increasing urgency to find and develop new renewable energy sources suggests a detailed examination of the suitability of flapping-wing machines for power generation since flapping wings can be used either for thrust generation or for power production. The difference between the two cases is shown in Fig. 3 where the difference in airfoil incidence angle relative to the flight path is shown leading to either thrust generation or power extraction from the air. Indeed, the second case merely represents the case of two-degree-of-freedom bending-torsion wing flutter, as can be seen more clearly from Fig. 4. In the upper figure the airfoil executes the same pitch-plunge motion as shown for the power extraction of Fig. 3. However, both the plunge velocity and the lift are indicated in Fig. 4. It is seen that the airfoil motion and the lift are always in the same direction throughout the complete oscillation cycle. Hence for the upper case (with a phase angle of 90 degrees between the pitch and the plunge motion) work is done by the lift on the airfoil. For the case of zero phasing, on the other hand, the lift opposes the motion during parts of the oscillation and zero net work is done on the airfoil. A more detailed examination of the thrust and power generation cases by means of unsteady incompressible flow analysis [2] shows that optimum thrust and power generation occur at a phase angle of 90 degrees between the pitch and plunge motions. The switch from thrust to power generation merely requires a significant increase in pitch amplitude.

4.1 The Jet Stream Power Source

It is well recognized that the Earth’s jet streams represent an enormous energy reservoir. These jet streams are fast moving air currents in the upper levels of the atmosphere, typically thousands of kilometers long, a few hundred kilometers wide and a few kilometers thick. They are usually found between 8 to 15 km above the earth’s surface. The wind speeds typically vary between 55 km/h in summer to

120 km/h in winter. Hence, the wind speeds available in the jet streams are typically two to three times higher than the average wind speeds near the surface of the Earth. Since the power output varies with the third power of the wind speed the reduction in air density with altitude is vastly compensated by the increase in wind speed. O'Doherty and Roberts [11] have shown that in the United States average power densities of around 17 kW/m^2 are available . Therefore, systems to exploit this power source will require a merging of the aeronautical and power engineering technologies in the form of developing flying electric generators.

4.2 Current Status of Flying Electric Generator (FEG) Technology

Flying electric generators have first been proposed in 1979 by Fletcher and Roberts [12] who explored the feasibility of mounting shrouded wind turbines on aircraft held in position by two tethers. More recently, Roberts et al [13] proposed the use of rotorcraft with four or more rotors tethered to the ground with single, composite electro-mechanical cables made of insulated aluminum conductors and high-strength fiber. The craft simultaneously generate lift and electricity.

The question arises whether oscillating wing power generators offer advantages over the rotary systems proposed in references [12] and [13].

4.3 Current Status of Oscillating-Wing Power Generation Technology

It is feasible to construct an oscillating wing power generator for the purpose of extracting useful power from a flow. In 1981, McKinney and DeLaurier [4] built such a device at the University of Toronto. It consists of a horizontally mounted wing whose plunging motion is transformed into a rotary shaft motion. The wing is pivoted to pitch at its half-chord location by means of a fitting which is rigidly attached to the vertical support shaft. Also fixed to the support shaft is the outer sleeve of a push-pull cable whose end pivots on a wing-fixed lever to control the wing's pitch. The up-and-down motion of the support shaft is transformed, through a Scotch-yoke mechanism, into a rotary motion of a horizontal shaft. This shaft, in turn, operates a crank at its far end which actuates the previously mentioned pitch-control cable. Hence the wing's pitching and plunging motions are articulated together at a given frequency and phase angle. Wind tunnel tests of this device showed that this type of power generator is capable of converting wind energy into electricity with an efficiency approaching that of conventional windmills.

In recent years, Jones, Davids and Platzer [15] and Jones, Lindsey and Platzer [17] built similar wingmills for use in water flows. Their first wingmill consisted of a hydrofoil that was able to move in a coupled pitch and plunge motion. The ninety degree phasing between the pitch and plunge motions was enforced by a system of push rods, phasing gears, swing arms and bell-cranks, described in detail in references [14] and [15].

Lessons learned from these first wingmill tests were incorporated in the design of the second power generator shown in Fig. 5. It employed two hydrofoils in a tandem arrangement. The hydrofoils oscillated with a ninety degree phase difference, such that the null spot of one coincided with the power stroke of the other, thereby making the generator self-starting regardless of initial hydrofoil positions. Also, the flywheel used on the first generator could be dispensed with because of the mutual reinforcement between the two hydrofoils. Otherwise, the control of the pitch angle of the hydrofoils was accomplished in a manner similar to the method used on the first generator. The water tunnel tests of this second generator showed that the tandem arrangement indeed leads to a much smoother running machine. Further details are given in references [16] and [17].

To our knowledge, there are as yet only two companies that have attempted to apply the above-explained principle of power extraction by means of oscillating hydrofoils to the generation of electrical power from tidal flows. The Stingray generator of Engineering Business

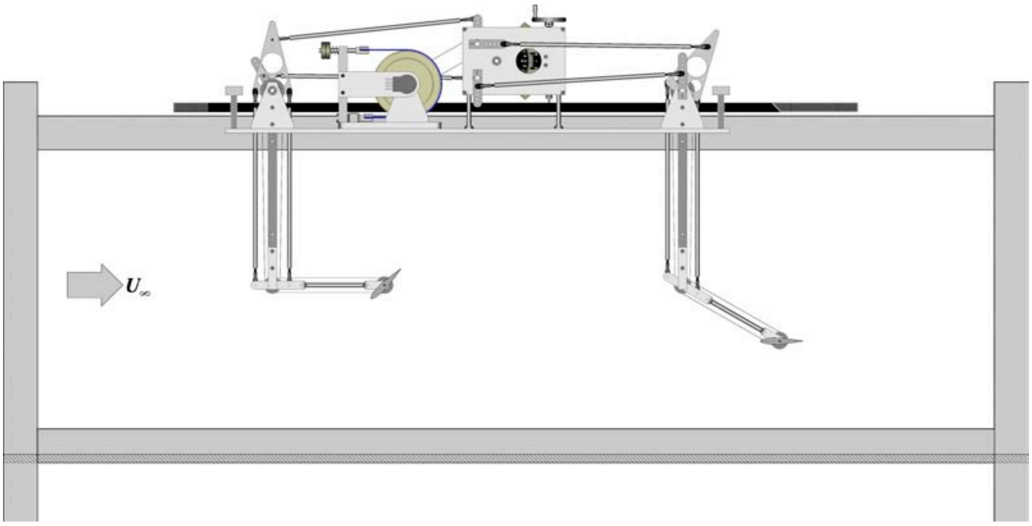

Fig. 5. Oscillating tandem-wing power generator [17].

Limited [18], founded in 1997 in the United Kingdom, uses a large hydrofoil which has both plunge and pitch degrees of freedom. It is attached to a structure which is bolted rigidly to the seabed. The generator was installed and tested in Yell Sound in September 2002. Power output was measured as 115 kW in a three-knot tidal stream. The project was supported by the British Department of Trade and Industry. The German company Aniprop demonstrated an oscillating-wing power generator that extracted 1 kW from the river Lech in the city of Augsburg [24].

4.4 Estimate of Power Output from Oscillating-Wing Power Generators

In the absence of experimental data we estimate the power output and the aerodynamic drag generated by an oscillating-wing power generator based on Navier-Stokes computations for two-dimensional flow over oscillating airfoils. These are briefly summarized in the next section. Previous two-dimensional Navier-Stokes estimates are due to Jones et al [17] and Kinsey and Dumas [19].

We denote the average power output per oscillation cycle and per unit of span as:

$$P = Cp \, \tfrac{1}{2} \, \rho \, V^3 c \qquad (2)$$

where Cp is the power coefficient, ρ the air density, V the wind speed, and c the airfoil chord. The computations yield power coefficients between 0.8 to 1.0 at optimum operating conditions. Hence at a wind speed of $V = 25$ m/s one obtains for a wing of 1 m chord length at sea level air density with a power coefficient of 0.9:

$$P = 0.9\,(1.225/2)\,(25^3) = 8613 \text{ W} \qquad (3)$$

Therefore the power output per unit span and unit chord is roughly 8.5 kW. At a wind speed of V = 30 m/s one obtains 14.9 kW. At altitudes of 6.5 km and 10 km, the air densities are 50% and 34% of the sea-level density. The power outputs per unit span and unit chord therefore are 4.25 kW at 6.5 km altitude and $V = 25$ m/s and 5 kW at 10 km altitude and $V = 30$ m/s.

4.5 Navier-Stokes Computations of Oscillating-Wing Power Output and Drag

Calculations were performed using a commercial numerical solver (Fluent) for a NACA0012 airfoil undergoing simultaneous plunging and pitching about the ¾ chord point. Each half-cycle of motion consisted of a constant velocity translation at fixed pitch angle, followed by a smooth reverse in direction and pitch angle. The plunge amplitude was fixed at 1 chord, and frequency chosen to give $Sr = 0.2$ for wind speed $V = 25$ m/s. The motion was characterized by the reversal time, ΔT_R, as a fraction of the total period (0.1 for rapid reversal, to 0.5 for fully sinusoidal motion) as shown in Fig. 6. The maximum pitch angle θ_{max} was varied from 15 degrees to 75 degrees. All motions were smoothed to remove jerk (discontinuous changes in acceleration).

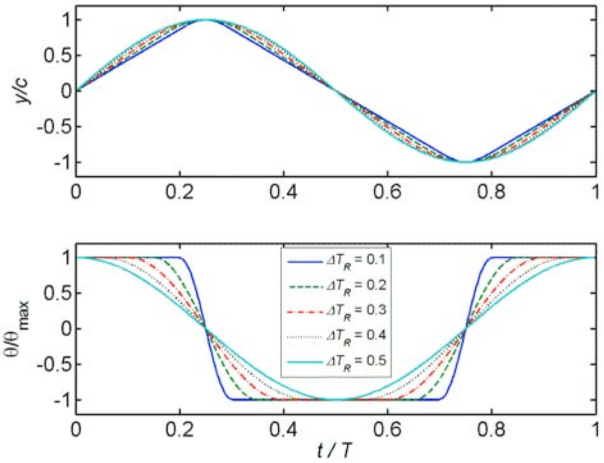

Fig. 6. Variation of simulated plunge and pitch motions.

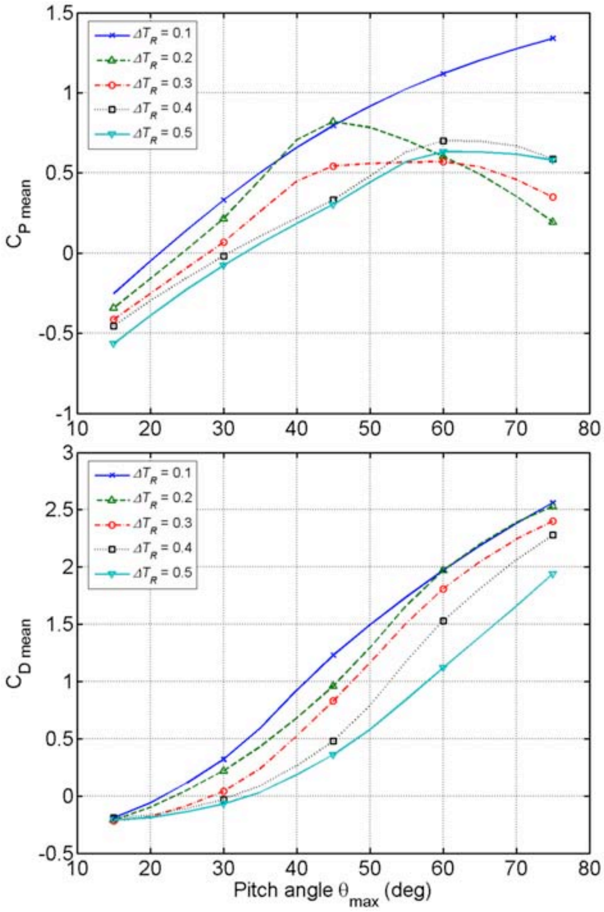

Fig. 7. Mean power coefficient and drag coefficient as a function of pitch angle and reversal time.

The results in Fig. 7 show that a power coefficient of 0.9 and a drag coefficient of 2.0 are feasible, and also show the advantage of a non-sinusoidal motion.

5 Types of Oscillating-Wing Power Generators

5.1 Mechanical Control of Pitch-Plunge Phasing

As already pointed out, a phase angle of about ninety degrees between the pitch and plunge motions of the airfoil is crucial for the extraction of energy from an air stream. As described above, McKinney and DeLaurier [4] and Jones et al [15,17] accomplished this by a suitable mechanical system of bell cranks, push rods and swing arms. Engineering Business Limited [18] used a hydraulic system to couple the oscillating hydrofoil motion to the electric generator.

5.2 Aerodynamic Control of Pitch-Plunge Phasing

More recently, we have developed an oscillating-wing power generator which requires no elaborate mechanism to enforce the wing's pitch-plunge motion at the proper phase angle between the pitch and plunge motions. This is made possible by mounting the wing on a swing arm which is supported by a bearing, thus allowing the swing arm to oscillate about the bearing axis with a finite angular amplitude. Furthermore, the wing is mounted on the swing arm in such a way that the wing can pitch about a pitch axis perpendicular to the swing arm. This pitch axis is chosen to be downstream of the wing's mid-chord point so that the wing's lift force always generates a moment about said pitch axis which tends to increase the pitch angle. It is well known that a symmetric wing (with zero camber) set in a flow at zero angle of attack induces a drag force in the flow direction but no lift force perpendicular to the wing. If the wing is forced to move, say to the right, then an angle of attack and therefore a force is induced which opposes the motion. However, if the wing is set at a large positive pitch angle prior to the motion to the right, a lift force to the right is induced. This lift force will be decreased due to the wing's motion to the right, but the motion to the right will continue as long as a net force to the right is maintained by keeping the wing's pitch angle sufficiently large. Hence work is done by the fluid on the wing during its motion to the right. This same effect occurs during the reverse stroke to the left if the wing is set at a sufficiently large negative pitch angle at the start of the reverse stroke. At the right stroke end point, therefore, the wing pitch angle must be reset as quickly as possible from a relatively large positive pitch angle (typically between 50 to 80 degrees) to a negative pitch angle of the same value and at the end of the stroke to the left, it must be reset from the negative pitch angle to the positive pitch angle.

The setting and maintenance of the required large positive or negative pitch angles during the right and left strokes, respectively, is accomplished by restraining the wing from exceeding the desired pitch angle by physical contact between the wing and a suitable contact surface. Furthermore, the wing will always be pressed against the contact surface, thus maintaining the desired pitch angle, because the pitch axis is located downstream of the mid-chord point and therefore an aerodynamic moment is generated which tends to turn the wing to its maximum possible pitch angle. Hence no separate mechanical system is required to enforce the proper pitch angle during the wing oscillation.

It remains to reset the pitch angle as quickly as possible at the stroke ends. This is again accomplished with the help of the air flow rather than by a mechanical system. To this end two switching rods are mounted in such a way that a spike attached to the wing leading edge starts to touch the right or left switching rod at the end of the right and left strokes, respectively. This forces the wing to rotate about the switching rod because an aerodynamic pitching moment is generated which changes the pitch angle from positive to negative on the right end of the stroke and from negative to positive on the left end.

In summary, the aerodynamically controlled oscillating-wing power generator is fundamentally different from previously demonstrated oscillating-wing power generators because no mechanical linkages are needed to induce a self-excited oscillation. Instead, the needed phase angle between the pitch and plunge oscillations of the wing is produced by purely aerodynamic means [20]. Other methods to generate the aerodynamic forces and moments necessary to produce the oscillatory motion described above are feasible, for example by means of control surfaces mounted on the wing.

6 The Flying Oscillating-Wing Power Generator

The above described mechanically or aerodynamically controlled oscillating wing power generator can be mounted on a suitable HALE aircraft which is tethered to the ground. For a first discussion, the power generator is assumed to consist only of one oscillating wing, although a dynamically balanced biplane arrangement is likely to be preferred. Furthermore, the oscillating-wing power generator is assumed to be mounted on a HALE aircraft similar in size and design to the Zephyr aircraft. Therefore, the wing is assumed to have a span of 20 m and a chord of 1 m. According to Thomas [21] a wing with a 144-39F3 profile can be flown up to lift coefficients of 2.2 at a drag coefficient of 0.015.The wing of the power generator is assumed to have a span of 10 m and a chord of 1m.

It is instructive to consider two flight conditions, namely a wind speed of 25 m/s at an altitude of 6.5 km and a wind speed of 30 m/s at an altitude of 10 km. At these two conditions the wing of the platform and of the power generator will be operating at Reynolds numbers of 978,000 and 866,625 respectively. The power generator will produce the following power outputs (using equation (2) and assuming a power coefficient of 0.9, based on 2-D flow estimates, for simplicity)

- At 6.5 km altitude and a wind speed of 25 m/s: $P = 43$ kW
- At 10 km altitude and a wind speed of 30 m/s: $P = 50$ kW

The drag caused by this power generator is estimated using a time-averaged drag coefficient of 2.0:

- At 6.5 km altitude and a wind speed of 25 m/s: $D = 3828$ N
- At 10 km altitude and a wind speed of 30 m/s: $D = 3749$ N

If the aircraft (without power generator) is assumed to fly at a lift coefficient of 2.0, then the lift is:

- At 6.5 km altitude and a wind speed of 25 m/s: L = 7656 N
- At 10 km altitude and a wind speed of 30 m/s: L = 7497 N

According to Fig. 106, p.80 of reference [21] the wing mass per unit area can be as low as 9 kg. Hence the weight of the wing is estimated to be 1800 N and the wing loading is 375 N/m^2. These weight and wing loading estimates are consistent with typical modern sailplane data (as listed by Thomas [21]). This leaves approximately 5700 N to support the platform (consisting mainly of a support beam to mount the oscillating-wing power generator, the electric generator and the horizontal and vertical stabilizers. To fly at a tether angle of 45 degrees, a lift component equal to the total drag must be generated. If the power generation drag is estimated to be approximately 3800 N and the aircraft drag 250 N (assuming an L/D ratio of 30) 1650 N remain available for the platform, the stabilizers, and the power and electric generators.

6.1 Tethering Cable

In the above estimate no account has been made of the weight of the tether. Roberts et al [13] estimate the tether's specific weight as approximately 115 kg/km. Furthermore, according to Fletcher & Roberts [12], the minimum tether weight occurs for tether slopes at the aerodynamic platform of 47 to 56 degrees depending on the conductor diameter. Hence for flight at altitudes of 10 km a tether weight approaching 2000 kg can be expected. It will therefore be necessary to equip the tether with one or more wings to provide it with a self-supporting capability. For example, if wings similar to the one used for the flying platform were attached to the tether, three such wings would be needed to provide the tether with a self-supporting flying capability at an altitude of 10 km.The tether is designed to transmit the electric power at a voltage of 15kV. For additional design and operational details we refer to references [12] and [13].

6.2 Additional Considerations

The foregoing discussion provides only a rough estimate of the expected performance of flying oscillating-wing power generators. It is apparent that the weight and cost of the tether are dominant parameters. They would make it unattractive to extract only 50 kW from the jet stream. However, multiple HALE aircraft with oscillating-wing power generators can be attached to a single tether to increase the jet-stream power extraction. Furthermore, mounting the tethers on high mountains will drastically reduce the required tether lengths and aerodynamically shaped tether profiles will improve the lift-to-drag ratios of the flying tethers.

The total vehicle weight and the drag generated by the oscillating-wing power generator are the key design parameters. Hence vehicle weight must be minimized by light-weight construction and sufficient lift must be generated to be able to fly at a tether angle of at least 45 degrees. This requires flight at a high lift coefficient. Some additional lift can be generated by inclining the power generator so that a lift component is being generated. Also, it may be possible to reduce the total drag. It was shown by Tuncer & Platzer [22] that a fixed airfoil mounted downstream of an oscillating airfoil generates a significant amount of thrust due to the Katzmayr effect [23]. Hence it may be worthwhile to mount an airfoil in the wake of the power generator or to place the power generator upstream of the HALE wing and to use the HALE wing as lift and thrust generator. Finally, it may even be attractive to mount the power generator on the solar-powered flapping-wing propelled HALE aircraft discussed in the section "Flapping-Wing High Altitude Long Endurance Vehicle", in order to reduce the drag of the aircraft.

7 Summary and Outlook

An analysis was presented to explore the potential of flapping-wing propellers and flapping-wing power generators for the development of high-altitude long-endurance (HALE) aircraft and flying electric generators. This analysis was motivated by the success of the flapping-wing micro air vehicle (MAV) shown in Fig. 1. The advantages identified during the development and flight testing of this MAV configuration appear to apply also to HALE aircraft because of the favorable propulsive and aerodynamic characteristics offered by the close-coupled wing/flapping propeller combination. Furthermore, the available information about flapping-wing power generators again indicates the feasibility and potential superiority of flapping-wing systems over previously proposed rotary power generators. However, systematic computational and experimental investigations are required to substantiate the exploratory study presented in this paper.

References

[1] Jones, K.D., Bradshaw, C.J., Papadopoulos, J., Platzer, M.F., Bio-inspired Design of Flapping-wing Micro Air Vehicles, *The Aeronautical Journal*, Vol. 109, No. 1098, August 2005, pp.385-393.

[2] Jones, K.D., Lund, T.C., Platzer, M.F., Experimental and Computational Investigation of Flapping Wing Propulsion for Micro Air Vehicles, Chapter 16 in Volume 195, *Progress in Astronautics and Aeronautics*, edited by T.J. Mueller, 2001, pp.307-339.

[3] Platzer, M.F. and Jones, K.D., Flapping Wing Aerodynamics – Progress and Challenges, *AIAA 2006-0500*, January 2006.

[4] McKinney, W. and DeLaurier, J., The Wingmill: An Oscillating Wing Windmill, *Journal of Energy*, Vol. 5, No. 2, pp.109-115, 1981.

[5] Young, J. and Lai, J.C.S., Mechanisms Influencing the Efficiency of Oscillating Airfoil Propulsion, *AIAA Journal*, Vol. 45, No. 7, pp.1695-1702, July 2007.

[6] Pendaries, C., Boiffier, J.L., Barreau, J.J., Jeanneau, M., Flexible Aircraft in Conceptual Design HALEs on the Way to Ornithopter, *AIAA 98-0505*, Jan. 1988.

[7] Betz, A., *Introduction to the Theory of Flow Machines*, Pergamon, New York, 1966.

[8] Smith, A.M.O., Roberts, H.E., The Jet Airplane Utilizing Boundary Layer Air for Propulsion, *Journal of the Aeronautical Sciences*, Vol. 14, No. 2, pp.97-109, February 1947.

[9] Smith, L.H., Wake Ingestion Propulsion Benefit, *Journal of Propulsion and Power*, Vol. 9, No. 1, pp.74-82, 1993.

[10] Kaya, M., Tuncer, I.H., Jones, K.D., Platzer, M.F., Optimization of Flapping Motion of Airfoils in a Biplane Configuration for Maximum Thrust and/or Efficiency, *AIAA 2007-0484*, January 2007.

[11] O'Doherty, R.J. and Roberts, B.W., The Application of U.S. Upper Wind Data in One Design of Tethered Wind Energy Systems, *Solar Energy Research Institute Report SERI/TR-211-1400*, February 1982.

[12] Fletcher, C.A.J. and Roberts, B.W., Electricity Generation from Jet-Stream Winds, *Journal of Energy*, Vol. 3, No. 4, July-August 1979, pp.241-249.

[13] Roberts, B.W., Shepard, D.H., Caldeira, K., Cannon, M.E., Eccles, D.G., Grenier, A.J., Freidin, J.F., Harnessing High Altitude Wind Power, *IEEE Transactions*, Vol. 22, No. 1, pp.136-144, March 2007.

[14] Davids, S.T., *A Computational and Experimental Investigation of a Flutter Generator*, MSAE Thesis, Naval Postgraduate School, Monterey, CA, June 1999.

[15] Jones, K.D., Davids, S.T., Platzer, M.F., Oscillating-Wing Power Generation, *ASME Paper FEDSM 99-7050*, 3rd ASME/JSME Joint Fluids Engineering Conference, July 1999.

[16] Lindsey, K., *A Feasibility Study of Oscillating-Wing Power Generators*, MSAE Thesis, Naval Postgraduate School, Monterey, CA, 2002.

[17] Jones, K.D., Lindsey, K., Platzer, M.F., An Investigation of the Fluid-Structure Interaction in an Oscillating-Wing Micro-Hydropower Generator, *Fluid-Structure Interaction II*, Wessex Institute of Technology Press, pp.73-82, 2003.

[18] The Engineering Business Limited (http://www.engb.com/).

[19] Kinsey, T. and Dumas, G., Parametric Study of an Oscillating Airfoil in Power Extraction Regime, *AIAA Journal*, Vol. 46, No.6, pp, 1318-1330, 2008.

[20] Platzer, M.F. and Bradley, R.A., *Oscillating-wing power generator with flow-induced pitch-plunge phasing*, Provisional US Patent US 61/002,883, Filing Date 11/13/2007.

[21] Thomas, F., *Fundamentals of Sailplane Design*, College Park Press, College Park, Maryland, 1999.

[22] Tuncer, I.H. and Platzer, M.F., Thrust Generation due to Airfoil Flapping, *AIAA Journal*, Vol. 34, No. 2, February 1996, pp.324-331.

[23] Katzmayr, R., Effect of Periodic Changes of Angle of Attack on Behavior of Airfoils, *NACA TM 147*, October 1922.

[24] http://www.aniprop.de

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