

Fundamentals of Energy Extraction from Natural Winds

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Abstract

When a bird or vehicle is oriented with a horizontal component of its lift vector aligned with the natural wind work is done on the flight system. Consequently, by suitable trajectories, variations in wind speed can be used to add energy to the system. These maneuvers are used by albatrosses and many other birds. An energy neutral cycle, defined as one where an unpowered vehicle returns to initial velocity and height, depends on the maximum lift/drag ratio of the vehicle and the wind speed variation. The minimum speed difference for a neutral energy cycle occurs for a vertical or horizontal step in wind speed. The equations of motion can be normalized by the minimum drag speed and have been solved numerically for an arbitrary wind profile. This solution is complicated and not provided here, but the results are discussed. In this paper a physical interpretation of the energy extraction mechanism is provided. Birds and small UAVs, with flight speeds comparable to atmospheric wind variations, can profit from wind energy extraction.

Introduction

Leonardo da Vinci observed and described the maneuvers of birds in natural winds in 1502, while conducting experiments aimed at building a man-carrying flying machine. He marveled at their ingenuity in using air movements to assist their flight as described by Domenico¹. Lord Rayleigh² described how the albatross of the Southern Ocean maneuvers to maintain altitude without flapping in winds with only horizontal flows, provided wind shear is present. So energy can be obtained from air motions with suitable maneuvers. Vehicles with low cruise speeds, of the order of 10 m/s, such as birds and small Unmanned Aerial Vehicles (UAVs), can benefit significantly from the use of atmospheric energy present in the form of spatial wind variation or turbulence, extracting energy from natural flows with no mean vertical component.

The dynamic soaring maneuver of pelagic birds, typically the albatross in the boundary layer of the Southern Ocean, is used to traverse thousands of kilometers with minimal energy expenditure. Their flight path has been studied by Sachs³ and Lissaman⁴. Sachs developed a variational procedure to optimize the control schedule for an unpowered vehicle operating in a linear wind profile (uniform gradient). He derived fundamental results for the minimum gradient required to execute a flight path, called an energy neutral *loop*, in which the vehicle returns to the original height and speed vector. In an extended analysis, Sachs and Mayrhofer⁵ analyzed the case of non-uniform wind shear, as obtained on the lee slopes of hills. For the fundamental Sachs case the vehicle does not return to its original position in inertial coordinates, but drifts downwind of its origin. Lissaman extended the analysis, showing that an energy neutral closed *cycle* can be flown such that the vehicle does, in fact, return to its original state and inertial starting point. This requires a slightly more intense wind gradient than the canonical case with downwind drift.

In regions of spatially varying wind energy can be extracted by a downwind turn, by a climb into wind, or by a downwind dive. A downwind turn is defined as one where the vehicle initially heading upwind executes a 180° banked turn to head downwind. In these cases the lift produces a force in the direction of motion, like a normal vehicle thrust system. Lissaman⁴ described this in a simple but sufficient “belly to the breeze” rule. These maneuvers can be accomplished by some control that changes *N*, the normalized aerodynamic force normal to the vehicle axis, and by banking the vehicle.

The exact expression for the motion of the vehicle can be obtained by integration of the equations of motion, as has been done in the cited references. There are few exact analytical expressions and these for quite restrictive cases. The present paper is written with minimum use of mathematics as a simple, physically accurate description of the process of energy extraction from the wind.

Simple cases of energy addition

Two fundamental maneuver cases are described here: the downwind turn and the upwind climb.

Mechanics of a 180° downwind turn

Consider a space fixed curved wall, or alcove, as shown in Fig. 1, and assume a ball, thrown into the right side at 10 m/s, returns out the left side at 8.0 m/s, with 2.0 m/s lost in friction. Friction causes a slight loss in energy of the system (if there were none, energy would be conserved) and there are forces on the alcove, but only friction work is done on the system. Now consider the same case, shown in the second diagram, where the alcove is moving, being pushed towards the thrower at 2.0 m/s and the ball is launched at 8 m/s. The ball dynamics on the alcove are identical to the first case, so that it emerges with an alcove relative speed of 8.0 m/s, and a ground speed of 10.0 m/s. The speed, and energy, of the ball has been increased, by 2.0 m/s. For zero friction the gain in speed would be twice the

alcove speed, 4.0 m/s. This is due to the work done in moving the wall against the forces produced as the ball rounds the alcove.

An identical dynamics situation occurs when a flight vehicle or bird executes a 180° banked downwind turn, as illustrated in Fig. 2. The first diagram shows the case in zero wind, the second that when the turn is executed in a head wind. The flight vehicle is assumed to have the same speeds as those given for the ball.

In this case, the ground speed of the vehicle is again increased by approximately twice the wind speed, less the speed loss due to dissipation caused by drag. The work done on the vehicle is equal to the horizontal component of the lift vector, coupled with the wind speed. It is seen that the lift vector is normal to the relative wind on the vehicle and inclined upwards, to provide lift. The higher the lift component in the horizontal direction, the larger the energy acquisition by the vehicle during the turn. If the vehicle enters the turn at 8 m/s ground speed, in a head wind of 2 m/s, with 2 m/s loss due to drag, it will complete the turn with a ground speed of 10 m/s.

If the vehicle, traveling down wind, now enters an airspace where the ambient wind flow is zero (a calm) it can execute another 180° turn so that its speed will drop to approximately 10.0 - 2.0 = 8.0 m/s. It will return to its original state with zero speed or height change.

If the speed loss is about 2.0 m/s for one 180° turn, then it is only necessary to operate between a calm and a wind speed of 2.0 m/s to execute a neutral energy cycle.

This is the basis of energy extraction due to turns in a wind. It is apparent that this has nothing to do with changing altitude, or laying off speed for height, as has been frequently suggested in discussions of this effect. It is evident that a speed change occurring at heights above or below the present height can be utilized.

Optimal turn states

The flight efficiency of the vehicle can be expressed in a single term, the maximum lift-to-drag ratio of the vehicle, called the glide ratio, defined as G here.

An unpowered vehicle can maintain height by laying off speed against the dissipation due to drag. For a 180° turn there is a minimum speed drop for a vehicle of given maximum L/D ratio and cruise speed (defined as the speed, V, at maximum L/D). In a banked turn there will be a certain energy lost during the turn. If the bank angle is increased, then the time for the turn is reduced, but the rate of dissipation is increased because of the increased induced drag. Consequently there will be an optimal bank angle for given vehicle glide ratio, G, for minimum speed loss in a 180° turn. The speed loss in a uniformly banked turn can be expressed in closed form as documented in Lissaman⁴ in which the various parameters of turn speed, glide ratio, and bank angle were investigated to determine the optimal bank assuming a constant height, constant bank turn. For a wind speed jump of ΔW and a

complete circuit it can be shown that the minimum value, ΔW, is given approximately by:

$$\Delta W = 4.75 V/G$$

Considered as a wind gradient, the above case, a wind speed jump occurring over zero height, can be regarded as an infinite wind gradient. Evidently for practical gradients, the vehicle has to reach a level of sufficient relative headwind (which may occur above or below the current height) to gain enough energy. The trajectory to the region of higher head wind must be selected to minimize loss during the passage. This indicates that there must be a minimum value of linear gradient for neutral energy trajectories, and a control schedule can be defined to accomplish this. This is discussed in a later section.

Mechanics of an upwind climb

If the vehicle inertial trajectory has a vertically upwards component, then the lift vector, that is normal to the relative wind, is inclined backwards, in the direction of the wind. This now contributes a component of force that can perform work on the vehicle. The mechanics of this can be visualized in moving ramp shown in Fig. 3.

To calculate the energy gain due to the wind in this case it is necessary to consider the total energy, $H_e = V^2/2g + h$, where V and h are measured relative to the ground, and g is the gravitational acceleration. Although many different trajectories are possible here, the significant item is the change in height over the period, Δh. For an initial speed of V, a final horizontal speed of V_f , a speed loss due to drag of V_d , and a wind speed of W by considering events in the frame of the wind, and where no work is done on the vehicle, it is clear that:

$$H_e^* = (V+W)^2/2g + 0 = (V_f + W - V_d)^2/2g + \Delta h$$

In the ground fixed frame, the initial total energy may now be written:

$$H_e = V^2/2g + 0$$

while the final total energy, H_{ef} , becomes:

$$H_{ef} = V_f^2/2g + \Delta h$$

For no dissipative energy loss, $V_d = 0$, and if V_f is set to be zero, the increase in total head is given by:

$$\Delta H_e = W V/2g$$

This is an upper bound for the energy that can be extracted from an upwind climb. This can be compared with the increase in total head for a downwind turn, which for no dissipative energy loss, is:

$$\Delta H_e = 2W V/2g$$

Coupling of wind with lift component

A force does work on a body, increasing its kinetic energy, when its point of application moves in the direction of the force. A trivial example is that an initially stationary beach ball blown along a beach by a wind acquires kinetic energy. In the case of a flight vehicle, if the wind is in the direction of the aerodynamic force then work is done on the vehicle. The major component of the aerodynamic force is the lift, since the drag force is about 1/G of the lift. Figure 4 demonstrates how the horizontal component of the aerodynamic lift force is oriented in the direction of the wind for the cases described above. In the figure the stippled arrow represents the wind, the cross hatched the lift vector.

Normalization of results

The lift, L, and drag, D, are normalized by dividing by the vehicle weight, W^* . The normalized lift is given by $N = L/W^*$, so that N is the normal acceleration of the vehicle. The normalized drag, D/W^* , for a parabolic polar is given by:

$$D/W^* = (Q + N^2/Q)/2G$$

where G, the glide ratio is the maximum lift drag ratio of the vehicle, and Q is the ratio of the dynamic pressure to that for minimum drag. Consequently the only parameters for any vehicle are G, defining the performance and V, the cruise speed at minimum drag. This speed, V, essentially defines the size and speed scale. If all speeds in the problem are normalized by V, then the results are independent of vehicle scale.

Equations of motion

The three equations of motion can be written in horizontal, vertical and lateral frames, using the inertial velocity (the ground speed) as the dependent parameter and including the angle of climb, bank, and yaw. An additional equation is provided by the airspeed, the vector combination of inertial vehicle speed and inertial wind speed. A ground fixed frame is necessary to maintain a proper inertial reference as the vehicle moves through regions of different wind.

The equations contain two control parameters that can be arbitrarily chosen, one is N, the normal acceleration, controllable essentially by elevator (tail or wing sweep for birds) and the bank angle, controlled by aileron (tail or wing twist for birds). These control inputs determine the vehicle motion. These equations are fully expressed in Lissaman⁴ and solutions provided in that paper.

A typical solution for these equations is shown in Fig. 5, for the case of linear wind gradient. The cycle is an open loop, not closed, in inertial space. For a closed cycle, possible with a slightly higher linear wind shear, as shown by Lissaman⁴, the ground track is nearly elliptical, as in Fig. 6. For a shear step, the ground track is roughly circular.

Limitations on maneuver parameters

In maneuvering upper bounds are imposed on vehicle speed, normal G load and lift coefficient. These limits are controlled by the skin structure, the wing structural strength and aerodynamic lift capability. Generally, practical limits are imposed on speed, corresponding to dynamic pressure, defined by Q, by skin structural factors relating to the never-exceed speed of the vehicle (about 2.5 for modern sailplanes), on N (= L^*/Q) by structural factors relating to wing bending (about 5 for modern sailplanes), and on L^* (the ratio of the operating lift coefficient to the cruise lift coefficient) by aerodynamic factors relating to maximum lift. L^* is about 2.0 for modern sailplanes. For birds these correspond to the flight speed limits, related to feather integrity, the pull-up load limit due to wing bone strength and the maximum lift coefficient, a function of wing aerodynamics. It is likely that these limits are lower for birds than for those of mechanical aircraft.

The limits can be identified in the engineering V-N envelope of a vehicle, where Q (actually shown as equivalent airspeed) represents the right hand boundary of the envelope, normally vertical, N the upper horizontal boundary on the right and L the quadratic upper left hand boundary.

Operating with N and the bank angle in the equations of motion, it is noted that extreme values of these parameters are required to maximize energy extraction. The physical reason for this is obvious: that the vehicle must maneuver into the region of energy-bearing wind as rapidly as possible to minimize normal drag dissipative losses. The limitations on the amount of G load pulled and bank angle are also clear, namely that at higher N and bank angles the lift requirements are larger so that the induced drag is increased. The optimum values of these are dictated by a trade-off between flying rapidly into a favorable wind field and not losing too much energy in doing so. The analyses for typical vehicles and wind profiles generally indicate that extreme N levels (exceeding 5) and banks (exceeding 70°) are required to obtain maximum energy capture.

Effect of wind profile

Two canonical cases are natural for study, since they do not require an arbitrary definition of the wind profile. The first is that of the wind step (infinite gradient), the second that of the linear wind profile (uniform gradient). The first requires the minimum speed jump across the trajectory, the second seeks the minimum gradient. Results for these cases have been quoted. Fundamentally, a speed increase from base to apex of the trajectory is required and the higher the vehicle must climb to reach this speed level the greater the dissipation losses in the trajectory.

Real boundary layer profiles are of neither of the cases quoted here, so the actual wind jump needed will lie between them. The normal boundary layer is closer to a speed step than a linear profile, so it is to be expected that the wind jump for the cases considered will be closer to the step than the uniform gradient.

The real cases considered are that of a typical oceanic profile, and that of ridge flow, where the vehicle is in stagnant flow for the lower part of its trajectory and emerges from the topographic (or building shelter) into the strong flow. These cases have been solved numerically and the magnitude of the speed jump calculated in each case. The normalized wind step is nearly inversely proportional to G , so that the generalized expression $G\Delta W/V$ for the wind jump has been used. These values are shown in Table 1. The magnitude of the “constant”, $G\Delta W/V$, provides a measure of the efficiency of the cycle.

Conclusions

Conclusions are as follows:

1. Energy can be extracted from the wind by executing a downwind turn, by climbing upwind, or by diving downwind. For a cycle with net energy gain, it is necessary to return through a region of lower wind than that where the energy was gained.
2. Simple mechanical trajectories have been described that are analogous to flight profiles for energy extraction from the wind.
3. It is not necessary for wind speed to increase with height to extract energy from the flow.

4. Vehicle performance is a function only of cruise speed and the maximum lift-to-drag ratio.
5. A wind speed change in the trajectory is required for energy extraction. The minimum occurs for a step change in wind speed over a vanishingly small height.
6. For typical oceanic boundary layer profiles and flow over ridges a modest change in flow speed is required, because the vehicle returns through a region of essentially calm flow.

References

¹Laurenzia, Domenico, *Leonardo on Flight*, Giunti Press, Florence - Milan, Italy, 2004.
²Lord Rayleigh, J. W. S., “The Sailing Flight of the Albatross,” *Nature*, 40, 1889, p. 34.
³Sachs G., “Optimal Wind Energy Extraction for Dynamic Soaring,” in *Applied Mathematics in Aerospace Science and Engineering*, Plenum Press, NY and London, Vol. 44, 1994, pp. 221-237.
⁴Lissaman, P. B. S., “Wind Energy Extraction by Birds and Flight Vehicles,” AIAA Paper 2005-241, Jan. 2005.
⁵Sachs, G. and Mayrhofer, M., “Shear Wind Strength Required for Dynamic Soaring at Ridges,” *Technical Soaring*, Vol. 25, No. 4, 2002.

Table 1
Maximum Wind Speed Factor for Basic Profiles

$G\Delta W/V$	Profile
4.75	Wind Step
4.95	Ridge Wind
6.22	Oceanic Wind
18.92	Linear Shear

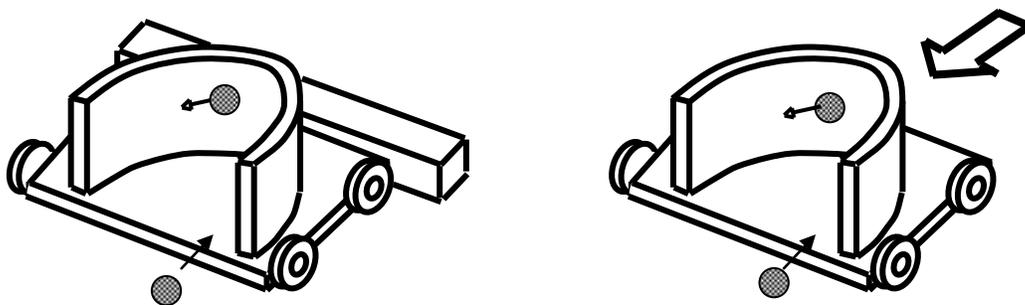


Figure 1 Dynamics of ball in alcove.

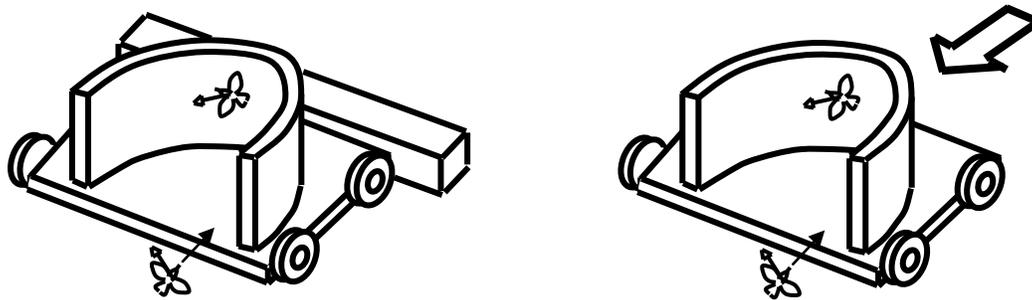


Figure 2 Dynamics of flight vehicle in downwind turn.

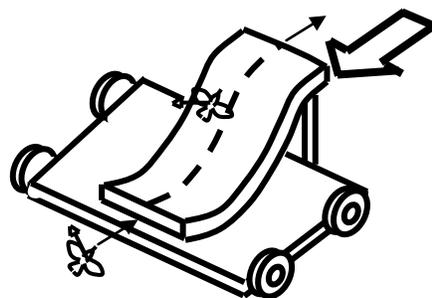


Figure 3 Dynamics of flight vehicle in upwind climb.

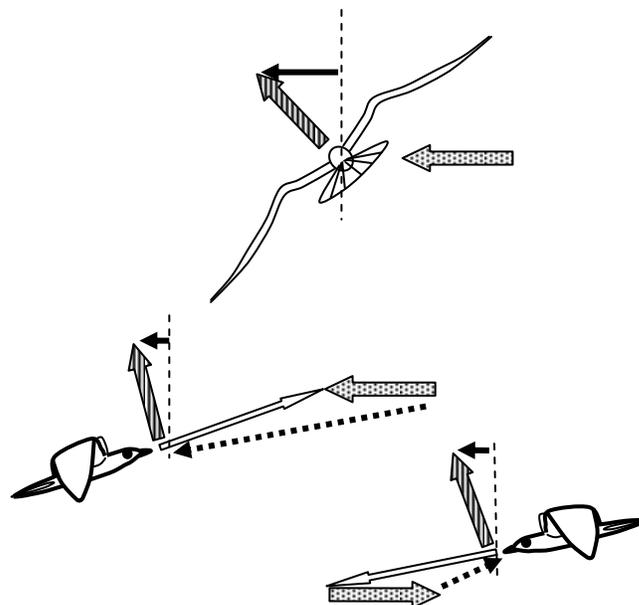


Figure 4 Windwise lift component for flight maneuvers.

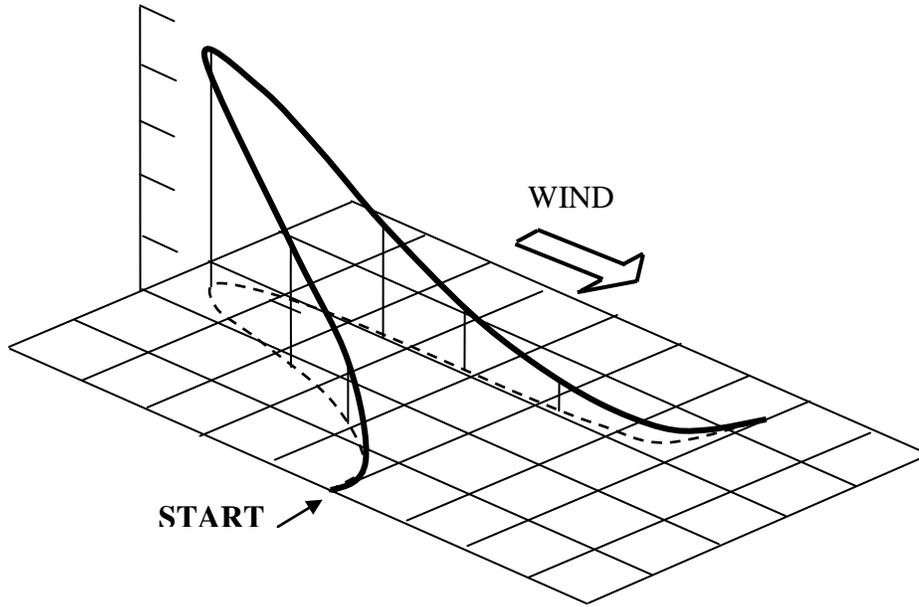


Figure 5 Typical trajectory for energy neutral loop in linear shear.

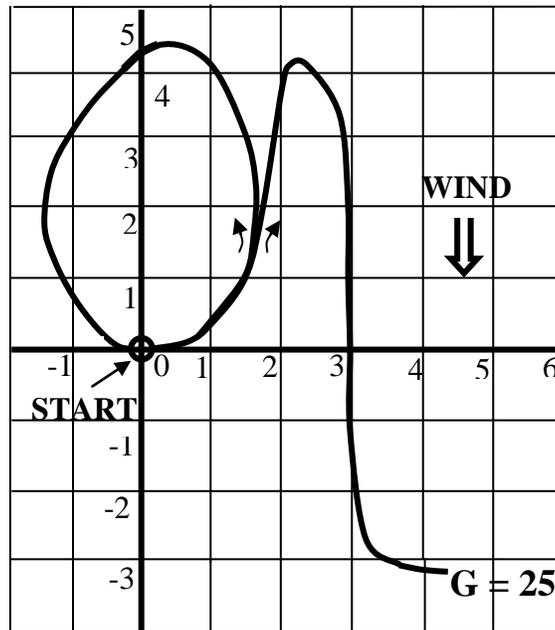


Figure 6 Ground tracks for fundamental open and closed trajectories.