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Simple Loitering Flight Path for High Altitude Uncrewed Aerial Vehicles

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Nomenclature

A	=	parameter defined in Eq. (8)
c_L, c_D	=	lift and drag coefficients, respectively
D	=	drag
k	=	parameter defined in Eq. (2)
L	=	lift
S	=	wing area
T	=	thrust
U	=	vehicle speed
$V, \delta V$	=	wind speed and wind speed difference, respectively
W	=	weight
w	=	vertical velocity component
γ	=	dive angle
ε	=	climb angle
ρ	=	atmospheric density
τ	=	fraction of time when windspeed is within a given range

Subscripts

0	=	nominal conditions
1	=	windspeed is less than the nominal aircraft speed
2	=	windspeed is greater than the nominal aircraft speed

Introduction

HIGH-ALTITUDE long-endurance (HALE) reconnaissance and telecommunications transponding missions are among the most significant tasks envisioned for uncrewed aerial vehicles (UAVs). There are several ongoing projects and different designs have been published, including solar powered[1] and hybrid propulsion vehicles.[2,3] The design for most of these is a very large, slow vehicle, flying at altitudes of 16–25 km (55,000–80,000 ft), where a worldwide minimum[4] in the westerly jetstream winds occurs, so that loitering, defined as staying in a given area, is least costly from an energetic point of view. Several studies have been made of the optimum trajectory for motions of such a slow UAV relative to the wind, to fulfill the requirement of keeping a fixed average position relative to the ground with defined limits on excursions. These were mainly driven by UAVs designed to be externally powered by microwave transmissions where the loitering requirement is essential. Thus, a figure-eight pattern[5] and oval[6] tracks have been suggested. Both of these require complicated maneuvering including banking angles during most of the time, which reduces the efficiency of solar panels.

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Technique

The present Note presents a much simpler and more effective loitering technique, which in principle allows the UAV to stay at a fixed position in a horizontal plane. This is based on the existance of a prevalent jetstream westerly wind at the altitudes in question.[4] To demonstrate the loitering technique, we assume that at any given time there is a westerly wind blowing, its velocity $V(h, t)$ varying as a function of height and time according to measurements such as appear in Ref. 4 (see also Fig. 1). As nominal conditions, the UAV is taken to fly at straight and level flight at a given altitude and known speed U_0 relative to still air. At this speed, we define nominal conditions

$$T_0 = D_0, \qquad L_0 = W \tag{1}$$

Using the regular definitions of the coefficients of lift and drag, we can write

$$W = kc_{L0}U_0^2, \qquad T_0 = kc_{D0}U_0^2 \qquad \text{where} \quad k \equiv \tfrac{1}{2}\rho S \tag{2}$$

Now taking the UAV to fly into an oncoming wind $V(t)$ (because h is fixed and known), we look at two separate cases.

For case 1, $V_1 < U_0$. This means that if the UAV were to fly at U_0, it would move westwards at speed $U_0 - V_1 \equiv \delta V_1$. Instead, we allow it to fly at speed V_1 (assuming $V_1 > U_{\text{stall}}$) but applying thrust T_0. This leaves extra thrust that is applied to climb. Assuming for simplicity that the climb angle ε is small, we can write

$$T_0 - W \sin\varepsilon = kc_{D1}(U_0 - \delta V_1)^2 \tag{3}$$

This assumption does not really constrain us because the thrust differences will not suffice for large climb angles anyway. This means that the changes in lift coefficient due to the climb angle are negligible. Subtracting the value of T_0 and dividing by W, from Eq. (2), and substituting the definition of $\sin\varepsilon \equiv w/V_1$, we obtain for the vertical velocity w

$$w_1 = V_1 \left\{ \left(\frac{c_{D1}}{c_{L1}}\right) \left[-1 + \frac{2\delta V_1}{U_0} - \left(\frac{\delta V_1}{U_0}\right)^2 \right] + \left(\frac{c_{D0}}{c_{L0}}\right) \right\} \tag{4}$$

In a similar fashion, for case 2, when the oncoming windspeed is $V_2 > U_0$, the UAV has to move at $V_2 = U_0 + \delta V_2$. If the UAV still

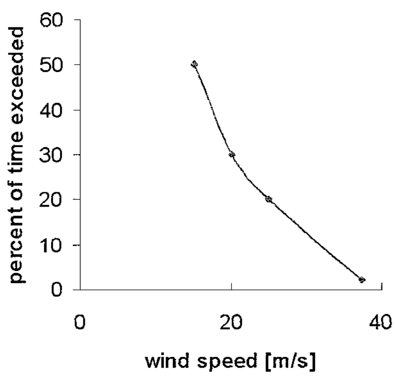

Fig. 1 Mediterranean winter windspeed histogram at 16–25 km altitude, adapted from Ref. 4; diamonds indicate data points.

uses the same thrust T_0, it will not be able to sustain level flight, but will have to dive at an angle γ such that

$$T_0 + W \sin\gamma = kc_{D2}\,(U_0 + \delta V_2)^2 \tag{5}$$

resulting in a vertical velocity w_2, which can be shown to be (again assuming small angles) by the earlier procedure

$$w_2 = V_2\left\{\left(\frac{c_{D2}}{c_{L2}}\right)\left[1 + \frac{2\delta V_2}{U_0} + \left(\frac{\delta V_2}{U_0}\right)^2\right] - \left(\frac{c_{D0}}{c_{L0}}\right)\right\} \tag{6}$$

The loitering maneuver can now be described. The UAV is pointed westward and flown at constant thrust T_0. At times when the oncoming wind is weaker than the nominal speed U_0, the UAV climbs with vertical speed w_1 while staying at the same position in the horizontal plane. On the other hand, when the oncoming windspeed is faster than U_0, the UAV sinks at vertical speed w_2, again staying at the same position in the horizontal plane.

Inspection and comparison of Eqs. (4) and (6) shows that w_2 is always greater than w_1. However, one can always find a speed U_0, for which the percentage of time τ_1 at which winds slower than U_0 blow is larger than that of winds stronger than U_0, τ_2, so that the average vertical excursion can be brought to be zero. Actually, the flight altitude and nominal speed U_0 for a given mission, or parts of it, thus should be chosen according to the local windspeed histogram.

Take as an example, $\delta V_1 = \delta V_2 \equiv \delta V$ and $c_{D2} = c_{D1} = c_{D0}$, which, while admittedly not accurate, allows an algebraically simple solution with no aircraft specific parameters. Then, for zero total vertical excursion,

$$w_1\tau_1 = w_2\tau_2 \tag{7}$$

where τ_1 is the time winds are blowing at $U_0 - \delta V$ and τ_2 is the time winds are blowing at $U_0 + \delta V$. From Eq. (7), substituting Eqs. (6) and (4), we obtain for $A \equiv \delta V / U_0$

$$Z = \frac{\tau_2}{\tau_1} = \frac{1 - A}{1 + A}\,\frac{2A - A^2}{2A + A^2} = \frac{2 - 3A + A^2}{2 + 3A + A^2} \tag{8}$$

The ratio of times required, Z, as a function of the speed excursion A appears in Fig. 2. In conjunction with Fig. 1 or similar data, this can now be used to establish the nominal velocity U_0 for any given area and time of year. Obviously, A should be small so the danger of stall is minimized, but not small enough so that every fluctuation in windspeed causes a change.

To clarify, a numerical example follows based on the specific conditions measured in the Mediterranean area.[4] The worst case in the Mediterranean area is in winter, where[4] at altitudes from 16 to 25 km, the windspeed exceeds 15 m/s 50% of the time, 20 m/s is exceeded 30%, 25 m/s is exceeded 20%, and 37.5 m/s is only reached 2% of the time (see Fig. 1). Thus, taking a nominal true airspeed for the aircraft of $U_0 = 32.5$ m/s we obtain, by interpolation, that dives will be required less than 6% of the time. On the other hand, taking an excursion in speed of 5 m/s (i.e., $A = \frac{5}{32.5} = 0.15$, approximately), we again obtain from the data that windspeeds will be in the range

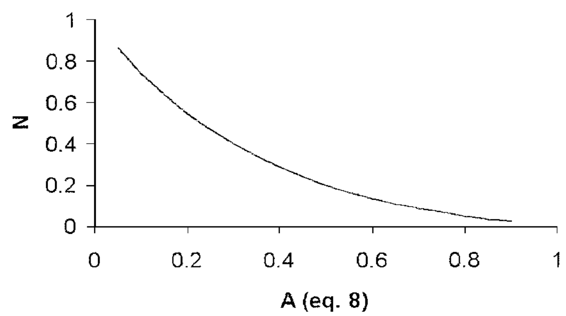

Fig. 2 Ratio of times required *Z* vs the normalized speed difference *A*, see Eq. (8).

27.5–32.5 m/s about 9% of the time. From Fig. 2, we see that for $A = 0.15$, $\tau_2/\tau_1 = 0.64$, which converges within 1% with the values obtained from Fig. 1.

Conclusion

Obviously, this loitering maneuver will need further tuning for specific cases using the full Eqs. (4) and (6). For hybrid and fully fueled long-endurance UAVs, the design point will also require adjustment for the reduction in weight due to fuel consumption during the mission, but this is shared with all other maneuvers mentioned and easily overcome.

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Baseline Validation of Unstructured Grid Reynolds-Averaged Navier–Stokes Toward Flow Control

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I. Introduction

THE value of the use of the Reynolds-averaged Navier–Stokes methodology for active flow control applications is assessed. An experimental flow control database exists for a NACA0015 airfoil modified at the leading edge to implement a fluidic actuator; hence, this configuration is used. Computational results are documented for the baseline wing configuration (no control) with the experimental results and assumes two-dimensional flow. The baseline wing configuration has discontinuities at the leading edge, trailing edge, and aft of midchord on the upper surface.

A limited number of active flow control applications have been tested in the laboratory and in flight. These applications include dynamic stall control using a deformable leading edge,[1] separation control for takeoff and landing flight conditions using piezoelectric devices,[2,3] pulsed vortex generators,[4] zero-net-mass oscillations,[5,6]

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