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The Turbulent Wind Environment of Birds, Insects and MAVs

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Abstract

Measurements are described that document the time-averaged and transient velocities at a height of 4m above the ground that provide insight into the turbulent flow environment of micro flight. These were made using a bank of four multi-hole probes laterally separated by 150 mms on a mast above a test car. Fluctuating pitch angles were investigated and it was found that the variation with lateral separation was significant, even under light winds, and that this did not reduce significantly as the separation reduced. This implies that the roll inputs arising from vertical fluctuations in the atmosphere would increase with reducing wingspan posing considerable control problems for man-made micro air vehicles.

Introduction and Aim

The natural world and the human constructed environment are significantly influenced by the atmospheric boundary layer (ABL) which extends from the ground surface to between 100 and 1000m, depending upon climatic conditions and terrain. The mean (time-averaged) and turbulent effects of the atmospheric wind in the ABL strongly affect the design of land-based structures and they also play a significant role in the design and operation of aircraft. In nature, the upper speed boundary of flight is set by a combination of the mean wind speed and gustiness inherent in the atmosphere. Atmospheric winds present a challenge to insects and birds – with the speed at which they curtail flying set by their capability to negotiate a desired flight path and/or strength limitations on their wings.

0.6 1	1	Light air	Butterflies
2 3	2	Light breeze	Gnats, midges, damselflies
4 5	3	Gentle breeze	Human-powered aircraft, flies, dragonflies
6 8	4	Moderate breeze	Bees, wasps, beetles, hummingbirds, swallows
10	5	Fresh breeze	Sparrows, thrushes, finches, owls, buzzards
	6	Strong breeze	Blackbirds, crows
	7	Near gale	Gulls, falcons
20	8	Gale	Ducks, geese
	9	Strong gale	Swans, coots
	10	Storm	Sailplanes
30	11	Violent storm	Light aircraft
	12	Hurricane	

Table 1 Flying Speeds of Insects, Birds and Aircraft

There is a considerable body of work on the flight speeds of birds and insects e.g. see Table 1, reproduced from [1]. Under relatively low wind speeds the smaller flying insects remain grounded, and as the wind speed rises, increasingly larger insects, then birds, then aircraft, become grounded. Tennekes [1] comments that there is a considerable difference between the maritime climate and a continental one thus ocean birds, living in a relatively windy environment, tend to have larger wingspans than their more continental counterparts.

Whilst the flying speed of birds and insects has received much attention, data on the turbulent flow environment is relatively scant. Much work has been done on understanding the turbulence inherent in atmospheric winds and its effects on the response of structures and large aircraft; see for example [2] but the small scale structures that are relevant to smaller flying birds and insects remain a mystery to those outside their world.

The design and use of Unmanned Air Vehicles (UAVs) are currently areas of significant interest, including miniaturizing and controlling such vehicles to meet the mission requirements for a wide range of commercial and military operations [3], [4] and [5] and currently there is strong interest on emulating the insect world including replication of a one-inch robotic fly [6].

Micro air vehicles (MAVs) typically have a spans that range from the fly scale to the larger birds. MAV operations are of relatively short flying duration and at low speed close to the ground. Thus they are "immersed" in the lower part of the ABL. Since MAVs are to be flown "over hillside, around street corners or up to a window for reconnaissance and surveillance" [3] they will be operating in the "roughness zone" where the wakes of the local surface obstructions are significant. The wind environment of cities is known to be complex and the wakes of ground-based objects can increase the turbulent energy levels. When the wind is present the operational environments of MAVs are turbulent; far more so than larger aircraft that cruise above the ABL.

Watkins demonstrated outdoor flight of aircraft of 65g, [7]. In addition to the prior documentation, personal experience has shown that the largest challenge to their flight is overcoming the effects of turbulence, particularly small vortices and eddies that are inherent in atmospheric turbulence that produce seemingly random roll and pitch inputs. This seems due to the relative size of structures in atmospheric turbulence as well as the effects the mean atmospheric wind. It is considered that this restriction would curtail the number of possible days per year that they could be used for outdoor activities.

The aim of the work reported here is to further the understanding of the turbulent flow environment by measuring the transient flow vectors at four laterally separated points in space corresponding to a "span" of 150 mms.

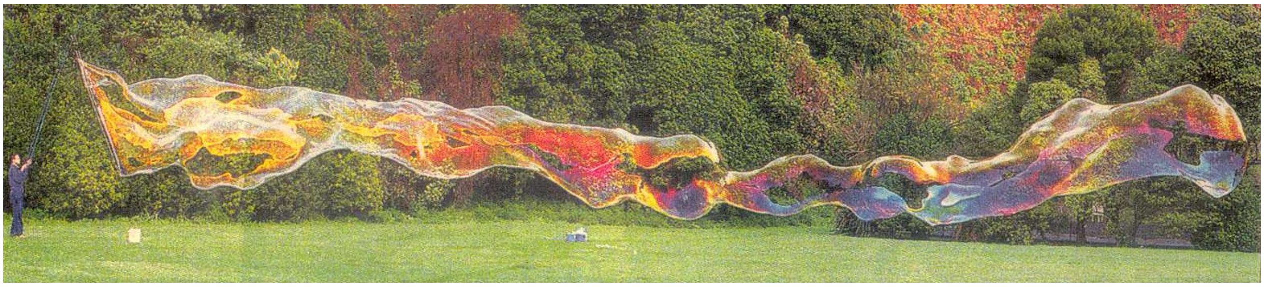

Figure One The Largest Bubble in the World (1998). Photo Courtesy Reuters.

A useful and interesting depiction of atmospheric turbulence very close to the ground is given above in Figure 1 (note the person standing in the left hand side for an indication of scale). Although surface tension effects minimise the influence of the extremely small structures in the atmosphere, distortion of the soap film depicts some of the smaller scale structures in the first few metres of the ABL that influence micro flight. The influence of various scale eddies are apparent, ranging from less than half a metre to approximately 15 metres (the total length of the bubble is 32 metres). Less evident, but arguably more significant to the flight of MAVs, is vorticity about a horizontal axis which is apparent one-third way along the length of the bubble and towards the end.

Multi-Point Measurements

Four TF[1] multi-hole probes of 3 mm head dimension were utilised with lateral separations of 150 mm, thus covering a 'span" of 450 mm, see Figure 2. The probes provide a more robust alternative to hot-wire anemometers yet, via a dynamic calibration, have a frequency and amplitude response that is flat from 0 to 2,000Hz and are accurate from a mean velocity of about 2-40 m/s. In turbulent flow the velocity vector is constantly fluctuating in angle and to enable resolution of the fluctuating vector the probes are calibrated over a cone of +/-45 degrees. Data that fall outside the acceptance cone are flagged by the software.

Figure 2 The Four Multi-Hole Probes

Details of pressure probe systems, verification and examples of use can be found in Watkins et al [8]. The probes were mounted 4.0 m from the ground on a mast above a vehicle and aligned nominally to the direction of motion, see Figure 3.

Calibration and Data Processing

The probes were calibrated by the manufacturer for velocity and frequency response. In order to measure the exact alignment angles of pitch and roll referenced to the horizontal and direction of travel, and to check the velocity calibration, runs were performed at 100 km/h (27.8 m/s) under calm conditions. The maximum variation in relative velocity averaged over each run between each probe (for several runs) was 0.3 m/s with a typical variation of 0.1 m/s. The maximum variations in averaged pitch and yaw angles between each probe after (minor) offsets had been removed were 0.2 degrees. The proximity effect of the car body on velocity and angle was not accounted for. However prior experience with sensors mounted closer to the car body than was the case for this work, had shown the proximity effect to be relatively minor and is not thought to significantly influence the results.

The four probes were simultaneously sampled at 6,500 Hz and to avoid aliasing data were filtered and down sampled to 375 Hz. This was thought to be a good compromise between excessive data capture and resolving frequency. Prior work had shown that under atmospheric winds of upto 9 m/s and a vehicle speed of 100 km/hr there is little turbulent energy above 100 Hz.

For the moving vehicle runs a sample length of 10 seconds was used. For documenting the atmospheric wind (ie when the vehicle was stationary) 100 seconds samples were used and these data were captured whilst the vehicle was parked close to the start or end of a moving run, on locations that were selected to be away from local effects (buildings, trees etc).

Arithmetic averages of the magnitude of relative velocities were calculated over the duration of each run to determine the average relative velocities. Turbulence intensities, in the three orthogonal directions, were calculated by dividing the standard deviation of each longitudinal, lateral and vertical fluctuation by the averaged relative velocity and expressed as a percent.

Test Strategy and Routes

The four sensors were "flown" along various roads in Victoria in order at 40, 60, 80 and 100 km/h either directly into or against the prevailing wind to obtain data relevant to a flying aircraft. Vehicle stationary (relative to the Earth) data were obtained in order to document the atmospheric winds. The terrain would be classed as category 2 in the Australian Wind Code ("open terrain with well scattered obstructions having heights generally of 1.5 to 10 m"). A large volume of data was recorded and only selected portions are presented here. These selected data were obtained during a 20 minute period and the vehicle stationary data sets (100 seconds duration) were obtained either side of the moving vehicle runs (10 second duration). For the data presented here the mean atmospheric wind was aligned to the road direction within 15 degrees and for most runs this was less than 10 degrees.

Results and Discussion

Time averaged data from the vehicle stationary tests indicated that the mean atmospheric wind Vw, was of 4-5 m/s in strength, details can be found in Watkins and Melbourne [9]. This is very close to the average windspeed at this height. The averaged outputs of each probe indicated that there was not a significant difference in mean speed between the four locations in space, but some slight variation in turbulence intensities was found The values of longitudinal, lateral and vertical intensities (denoted Iu, Iv and Iw) are close to the (limited) existing atmospheric data considering the height of the probes and terrain.

Single point velocity spectra (obtained from one probe output) were found to be closely similar to a von Karman spectra for atmospheric turbulence at this height, Figure 3

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[1] Turbulent Flow Pty Ltd

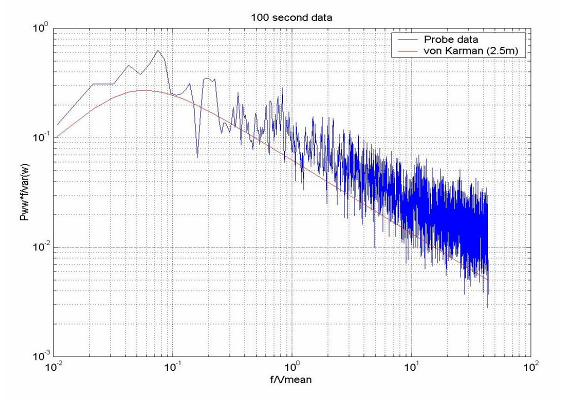

Figure 3 A Typical Spectrum from a Single Probe

Once motion is imposed (via moving the vehicle and probe system) the relative fluctuation magnitude experienced by the relative motion are reduced and the frequencies are increased. Figure 4 shows the relative turbulence intensities for the three orthogonal directions relative to the average direction of flight.

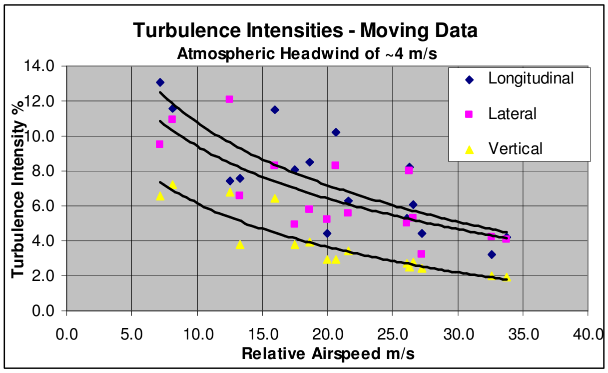

Figure 4 The Influence of Velocity on Turbulence Intensities

For 8 m/s air speed (which is a reasonable flying speed for small birds, see Table 1) relative turbulence intensities are of the order of 7 to 12%. It is interesting to note that for zero forward motion (but still subject to atmospheric winds) a hovering craft and a building will be subject to the same levels of atmospheric turbulence. In the field of building aerodynamics it is considered mandatory to simulate turbulence, whilst for aeronautical testing zero turbulence is strived for!

Time Histories

For selected data sets the instantaneous velocities and pitch angles are presented. Figure 5 and 6 show the variation of velocities and pitch angles for all four probes as a function of time for case of an 8 m/s flight speed through 4m/s atmospheric winds. Immediately apparent is the large variation in velocity and pitch angles (+/- 15 degrees) with time but all measurement points appear to have instantaneous velocities and pitch angles that are reasonably well correlated. However closer examination reveals that there are considerable differences pitch angles – Figure 7 depict short sections of data. At times there are differences in pitch angles of 20 degrees between Probes 2 and 3 which are laterally spatially removed by 150 mms. This is far greater than experimental error (estimated to be less than one degree).

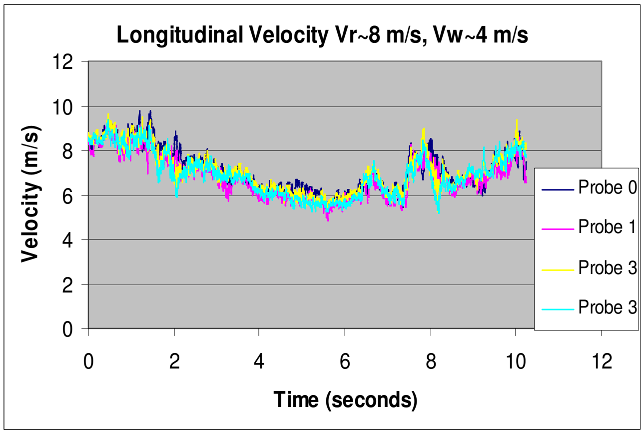

Figure 5 Longitudinal Velocity Time History

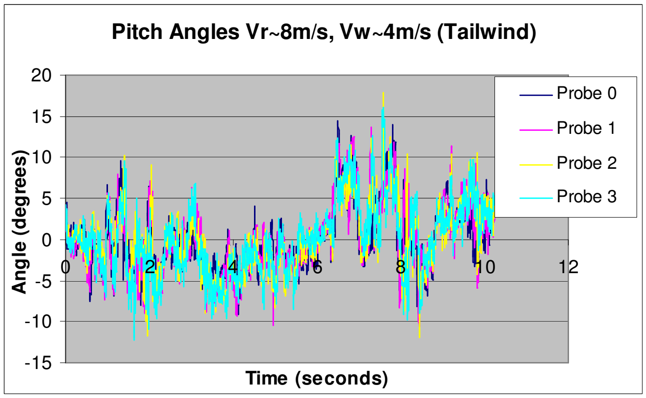

Figure 6 Pitch Angle Variation with Time

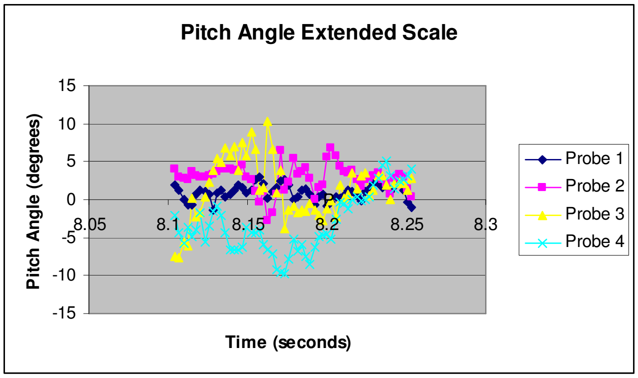

Figure 7 Pitch Angle Variations – Expanded Scale

It is useful to examine the variations in flow pitch angles that would be incident across the span of a MAV, in order to understand transient rolling moments. Plotted in Figures 8 to 10 are the differences in pitch angles between Probe 0 and Probes 1, 2 and 3 respectively for the first data set in Table 2. It can be seen that there seems little difference in variation as a function of lateral spacing.

The standard deviation of variation in pitch angles as a function of spacing is shown in Figure 11. The results for all combinations of probe spacing are plotted but are not readily evident since the points are almost coincident (eg for 150 mm separation data there are 3 data points arising from the three possible data sets Probe 1-0, Probe 2-1, Probe 3-1). It is interesting to speculate on the pitch angle differences at spacings less than 150mm or greater than 450mm.

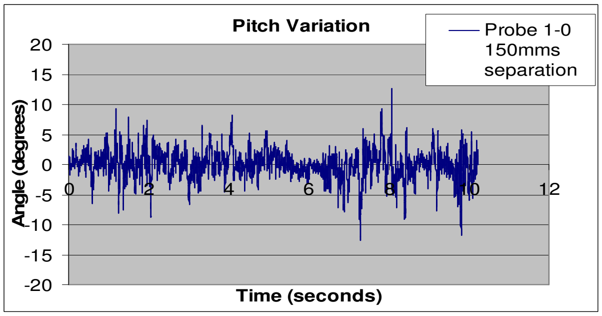

Figure 8 Pitch Angle Variation 150 mms Separation

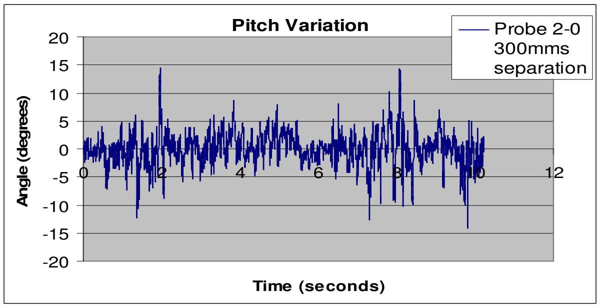

Figure 9 Pitch Angle Variation 300 mms Separation

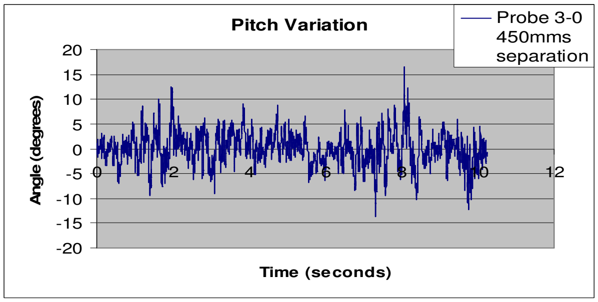

Figure 10 Pitch Angle Variation 450 mms Separation

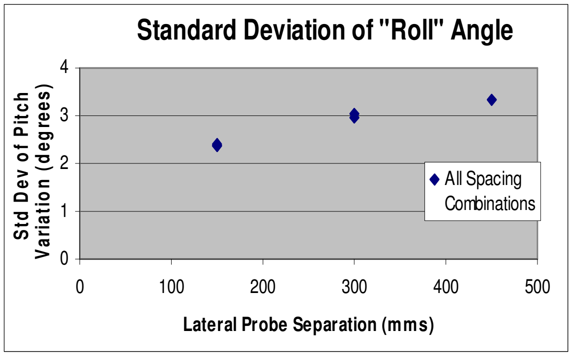

Figure 11 Standard Deviations of Pitch Variation vs Separation

Conclusions

Atmospheric conditions can vary from calm to cyclonic. Under no wind conditions the flight environment is smooth (aside from the wakes of other moving objects) whereas at the other extreme even large aircraft remain grounded. However days of zero or very low atmospheric winds are rare. An examination of the probability distributions of wind speed for one site[2] reveals that that most probably wind speed is approximately 4 m/s and average wind speeds below 2 m/s occur for less than 10% of the time. Clearly distribution varies with location height, terrain etc.

Further processing of the data sets gathered here is planned, including investigation of the effects of the turbulence on the motion of MAVs (from measured aerodynamic derivatives). High speeds and high masses will minimise aircraft motion through the ABL but this is in direct conflict with low speed manoeuvrability.

Unlike the majority of wind engineering data sets, the measurements taken here were for elevations that were close to the height of the ABL roughness zone. It should be noted that this is the environment in which MAVs are envisaged to collect data. Since the proposed environment of MAVs is through irregular terrain such as city canyons where very disturbed flow environments exist further work is considered necessary .

It is interesting to note that the variation in pitch angles with lateral separation (a parameter that is thought to influence the roll controllability of aircraft) is complex and that reducing separation from 450mm to 150mm appears to make relatively little difference to the variation, indicating that the roll rates induced by turbulence would increase as span reduces. Further work in this area is planned, including reducing the lateral spacing of the probes to 37.5 mm and analysing an existing data set obtained with a longitudinal probe separation, in order to understand the correlation of disturbances over aircraft of various spans and tail moments.

The potential roll inputs are of such significance it is postulated that it will be very hard to hold a relatively stable viewing platform. Clearly we have some way to go before we can emulate small-scale natural flight and how it has its adapted to the turbulent wind environment.

References

1. Tennekes H., “The Simple Science of Flight”, MIT Press, ISBN 0-262-70065-4
2. Holmes J. D., “Wind Loading of Structures”, Spon Press, London, 2001, ISBN 0-419-24610-X.
3. Burger, K., “Micro Air Vehicle Demo Approaching”, Janes Defence Weekly, Janes Publications, UK, Vol 36, Issue No 14, pp 6, 12 September 2001.
4. Burger, K., “Budget Boost for UAVs and Counter-terrorism”, Janes Defence Weekly, Janes Publications, UK, Vol 37, Issue No 1, pp 6, 2 January 2002a.
5. Anon “UAVs Applications are Driving Technology – Micro Air Vehicles”, UAV Annual Report, Defence Airborne Reconnaissance Office, Pentagon, Washington, pp 32, 6 November 1997.
6. Wilson and Schnepf, “Micro Air Vehicles – New Military Capability”, proc. 16th Int Conf on UAVs 2-4 April 2001, Bristol, UK.
7. Watkins S., “Development of a Micro Air Vehicle”, The Aeronautical Journal, February 2003.
8. Watkins S, Mousley P and Vino G., “The Development and Use of Dynamic Pressure Probes With Extended Cones of Acceptance (ECA)”, 14th AFMC, Sydney, Dec 2004.
9. Watkins S. and Melbourne W. H., “Atmospheric Turbulence and Micro Air Vehicles”, 18th Bristol International Conference on UAV Systems, Bristol University, UK, March 31 - April 2, 2003.
10. Watkins S and Saunders J. W., “A Review of the Wind Conditions Experienced by a Moving Vehicle”, SAE Technical Paper 981182 in *Developments in Vehicle Aerodynamics,* 1998, ISBN 0-7680-0138-2

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[2] Obtained over 42 years at a height of 10m for a site in Australia, see Watkins and Saunders [10]