

Span-wise wind fluctuations in open terrain as applicable to small flying craft

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ABSTRACT

Micro air vehicles (MAVs) are typically of low mass and moment of inertia and have flight speeds comparable to birds and the larger insects. Such craft traverse the lower levels of the atmospheric boundary layer (ABL) which is a significantly different environment than that experienced by larger manned aircraft, which spend the majority of their time in relatively clean air and fly at speeds significantly higher than typical wind speeds in the ABL. Here a new series of measurements dedicated to understanding spatial and temporal velocity fields that MAVs experience are presented. Atmospheric wind measurements were taken by sampling four multi-hole dynamic pressure probes spanned perpendicular to the oncoming wind at spans of between 0.014m and up to 0.45m. It was noted that the variation of both longitudinal velocity and flow pitch angle against spacing followed a fractional power law and as such large variations were present even for the smallest inter-probe separations. This effect is thought to explain the increasing piloting difficulties experienced in maintaining good roll control for decreasing scales of craft.

NOMENCLATURE

α	angle of incidence ($^{\circ}$)
α_T	'trim' angle of incidence ($^{\circ}$)
C_L	coefficient of lift
L	lift force (N)
L_T	'trimmed' lift force (N)
ρ	density (kg/m^3)

S	surface area (m^2)
$\sigma_{\Delta V}$	structure function(velocity vector) (ms^{-1})
$\sigma_{\Delta\alpha}$	structure function (angle of incidence) ($^{\circ}$)
$\sigma_{\Delta CL}$	structure function (lift coefficient)
u	velocity component (along wind) (ms^{-1})
V	velocity vector (ms^{-1})
v	velocity component (across wind) (ms^{-1})
w	velocity component (vertical) (ms^{-1})

1.0 INTRODUCTION

The Atmospheric Boundary Layer (ABL) is the lowest part of the atmosphere; it is the region of air that is influenced by the frictional effect of the surface of the Earth and it generally extends up to a height of about 1,000m depending on terrain and climatic effects, this is shown in Fig. 1 which gives typical mean velocity profiles of the wind over different terrain. As such, the turbulence levels within the ABL are much greater than at higher altitudes and can influence everything that flies within it, both natural and manmade. The amplitude of response of an aerofoil to a changing velocity increases as the wavelength of the velocity fluctuation increases relative to the aerofoil chord length⁽¹⁻²⁾. So for the general case as the size of flight vehicles reduces the more responsive they are to gusts. Large aircraft are only significantly influenced by a large gust. In contrast a small unmanned aircraft, or bird with much smaller moment of inertia and virtual mass, will be perturbed by much smaller gusts.

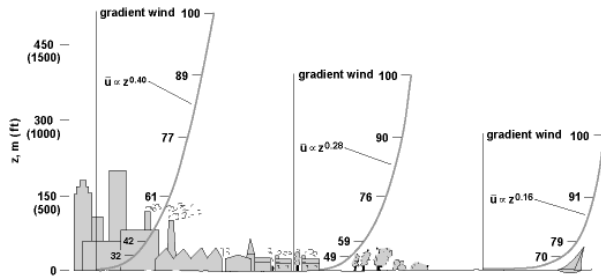


Figure 1. ABL profiles over different terrains. Wind speeds are expressed as percentages of the upper level wind above the ABL⁽³⁾.

In 1995 the Defense Advanced Research Projects Agency (DARPA) issued specifications supporting research into MAVs⁽⁴⁾. Between 1995 and 2010 many designs and prototypes have been built⁽⁵⁾ and while these aircraft can achieve good range and endurance performance they struggle to maintain straight and level (SL) flight in gusty conditions⁽⁶⁾. In particular, good control about the roll axis is a challenge⁽⁷⁾. Envisaged mission profiles require flight relatively close to the ground and often in complex terrain (e.g. cities) thus can be subject to highly turbulent air, such as experienced in the wakes of buildings. The purpose of such missions is recording and transmitting information – often visual. The ability to hold SL flight is an important requirement since the information needs to be clear to be useful. The challenge of overcoming atmosphere turbulence will increase with the more recent release of specifications for a Nano Air Vehicle (NAV) in 2000 (< 0.15m wingspan, < 20g)⁽⁸⁾.

Table 1
Classification of effective terrain roughness⁽¹¹⁾

#	Category	Surface roughness length, z_0	Landscape Description (H : obstacle height, x : obstacle separation)
1	Sea	0.0002m	Open water, featureless flat plain fetch (the upstream terrain) > 3 km
2	Smooth	0.005m	Obstacle-free land with negligible vegetation, marsh, ridge free ice
3	Open	0.03m	Flat open grass, tundra, airport runway, isolated obstacles separated by >50H
4	Roughly Open	0.1m	Low crops or plant cover, occasional obstacles separated by >20H
5	Rough	0.25m	Crops of varying height, scattered obstacles separated by $x \approx 12-15H$ if porous (shelterbelts) and $x \approx 8-12H$ if solid (buildings)
6	Very Rough	0.5m	Intensively cultivated landscape with large farms, orchards, bush land, $x \approx 8H$; low well-spaced buildings and no high trees, $x \approx 3-7H$
7	Skimming	1.0m	Full similar height obstacle cover, $x \approx H$, e.g. mature forests, densely built town area
8	Chaotic	>2.0m	Irregular distribution of very large elements: high rise city centre, big irregular forest with large clearings

It is important then that the wind environment be understood and taken into account when designing MAVs/NAVs that will be useful over a high number of days per year – not just when the wind gusts are insignificant. Despite this, little work has been done on understanding the likely aerodynamic inputs from gusts on very small aircraft flying at very low altitudes other than by Watkins, Milbank, Loxton and Melbourne⁽⁹⁾. To understand this area and to be able to determine the likely pitch, roll and yaw inputs for such an aircraft, simultaneous wind velocity measurements at multiple points across a virtual span (proportional to that of the aircraft size of interest) are required. These need to be recorded with sufficiently compact instruments and at a sufficiently high frequency to ensure adequate spatial and temporal resolution. The concept of taking measurements with laterally separated probes to document the aerodynamic inputs of turbulence on aircraft is not new. In a Wright Brothers Memorial Lecture, Etkin⁽¹⁰⁾ suggested the idea in order to study the effects on manned aircraft taking off and landing in windy conditions.

Table 1 is used in the discipline of wind engineering to categorise terrain conditions. The vertical profiles of time-averaged velocity and turbulence intensities can be estimated for the different terrains⁽¹¹⁾. It is useful to consider a likely mission profile for an MAV within these categories. Take-off is likely to be from an open area (category 3-4); the aircraft flies from here through increasingly complex terrain (category 5-6) to conduct a surveillance type mission in an area where line of sight is not possible (category 7-8) before returning to the take-off point.

This paper details the first of a series of new measurements documenting wind velocities applicable to MAVs. These are winds corresponding to those most common in the lower atmosphere, with mean wind speeds less than 10ms^{-1} and turbulence that has been generated by the mechanical mixing induced over a long fetch (the upstream terrain). No consideration is given to extreme wind conditions in which MAV (and bird and insect) flight will not, for the general case, be attempted. The measurements are analysed by calculating a variation (the standard deviation as opposed to the variance of the velocity difference is taken) on the lateral structure functions⁽¹²⁾ for the longitudinal velocity and the pitch angle. This is to enable comparison with previous data taken by Watkins *et al.*^(9,13,14).

‘Open’ terrain measurements (Table 1) are presented here which is the least complex terrain type expected for MAV flight but provides a starting point to develop and refine methods of analysis. Further measurements in increasingly complex terrains including ‘Chaotic’ city centre terrains, where MAVs are likely to be most useful are planned. Measurements were taken at a height of two metres and covered spans of lateral separation 0.015m to 0.45m. This work is part of a larger program focused on the flight of MAVs in turbulent conditions, a summary of which can be found in Watkins, Abdulrahim, Thompson, Shortis, Segal and Sheridan⁽¹⁵⁾.

The results are analysed to investigate the longitudinal velocity and pitch angle variations of the wind over these spans, in order to provide insights into the challenges of flight at small scale. The purpose of this research is to look at the potential roll inputs from atmospheric turbulence arising as the result of unequal lift forces on each wing. The data should also prove useful for providing a test environment, either replicated or simulated, that encompasses a good replication of the turbulent environment. It may also be of interest to avian biologists and others studying the flight of animals and insects.

2.0 EXPERIMENT DESCRIPTION

2.1 Location

The results presented here were taken at $51^{\circ}45'20''\text{N}$ $3^{\circ}55'50''\text{W}$, a location in the Lliw Valley of Southern Wales between Clydach and Ammanford, The test site is in a nominally level area surrounded by undulating terrain as can be seen in Fig. 2. The fetch



Figure 2. Fetch at test location.



Figure 3. Satellite image of location.

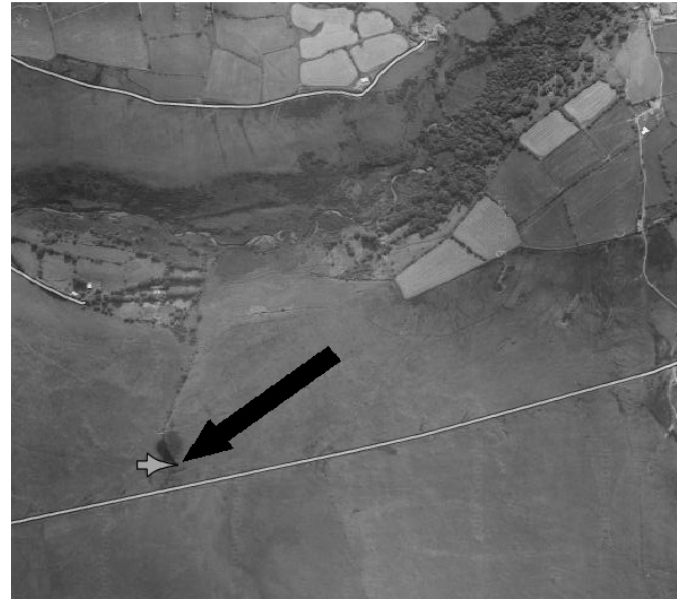


Figure 4. Topographical overview of location.

for 1km upwind of the probes can be described as terrain category 3 (see Table 1). A satellite image and topographical map are given in Fig. 3 and Fig. 4 respectively, the point marked 'A' is the test location and the arrow indicates the wind direction (South East).

2.2 Instrumentation

Four four-hole pressure probes, known as TFI Cobra probes⁽¹⁶⁾, of 2.6 mm head dimension were mounted on a lateral cross-head. This was horizontal and positioned across the mean wind direction to permit various inter-probe separations. The cross-head was then attached to a mast such that the probe heads were 2m above ground

level and aligned into the time averaged wind direction, see Fig. 6. Multi-hole probes were used because they provide a more robust alternative to hot-wire anemometers and have a frequency response that is flat from 0 to 2,000Hz. The probes were able to resolve the three orthogonal components of velocity and provide the static pressure, providing the flow vector was contained within a cone of $\pm 45^\circ$ around the x -axis of the probe. This enabled resolution of the constantly fluctuating velocity vector in turbulent flow, providing each probe was approximately aligned with the along-wind (x) axis flow direction and the turbulence intensities were not excessively large. Prior measurements demonstrated that if the longitudinal turbulence intensity is less than 30% of the velocity vectors remained within the cone of acceptance. This was the case for all

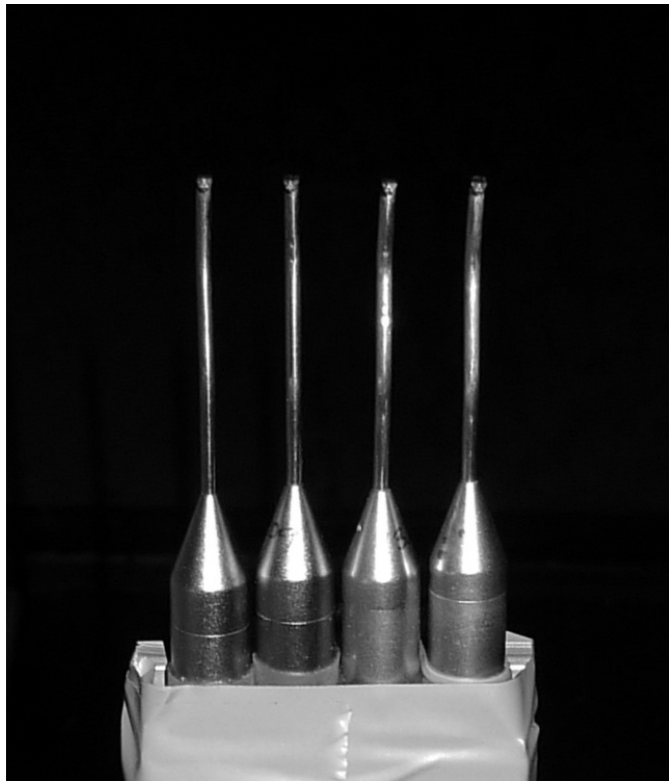


Figure 5. 0.014m inter-probe spacing.

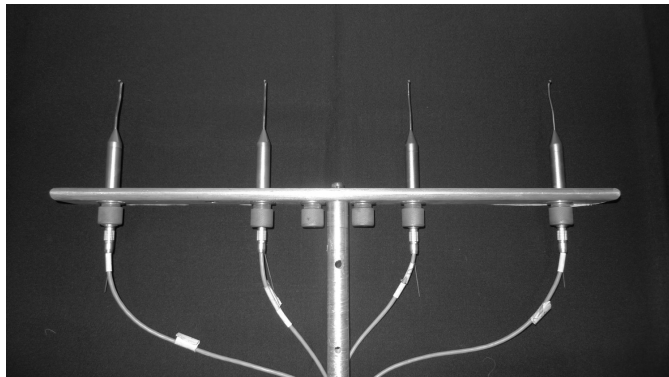


Figure 6. 0.15m inter-probe spacing.

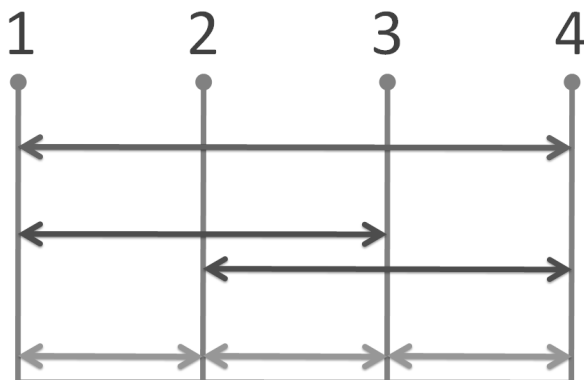


Figure 7. Probe spacing combinations.

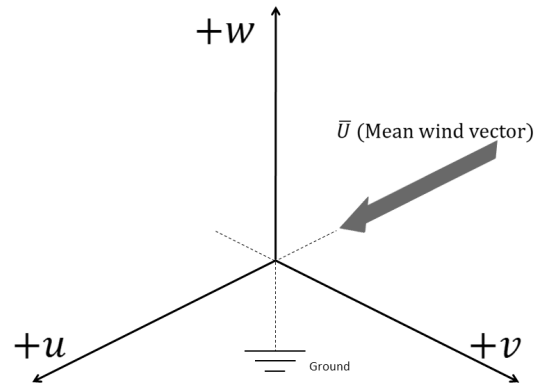


Figure 8. Definition of velocity components.

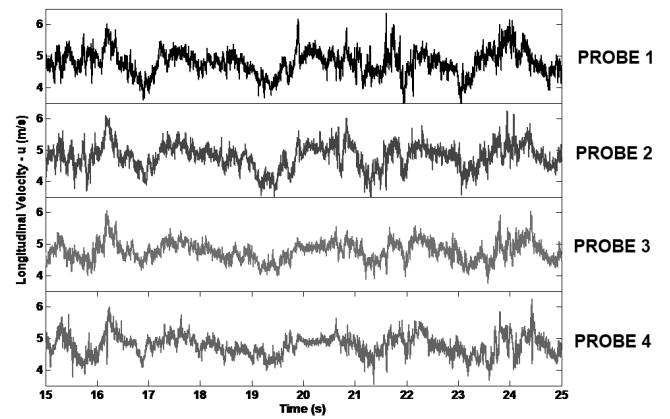


Figure 9. Longitudinal velocity of four probes over 10s (0.15m interprobe spacing).

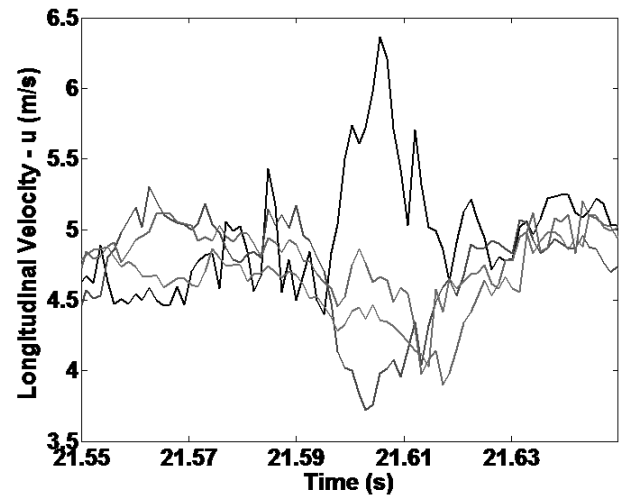


Figure 10. Longitudinal velocity of four probes over 0.1s (0.15m interprobe spacing).

the measurements reported here. Details of the system and examples of use can be found in Watkins, Mousley and Hooper⁽¹⁷⁾ and verification and further details including dynamic capabilities, probe operation methodology and calibration techniques can be found in Hooper and Musgrove⁽¹⁸⁾ and Chen, Haynes and Fletcher⁽¹⁹⁾. Although not used here a similar technique, with a 13 hole pressure probe, enables the cone of acceptance to extend to $\pm 135^\circ$ ⁽²⁰⁾.

Table 2
Possible spacing combinations

Distance between probes (m)	Spacing combinations (m)		
0.014	0.014	0.028	0.042
0.05	0.05	0.1	0.15
0.15	0.15	0.3	0.45

2.3 Test procedure and data analysis

(The following sections use the notation set out in Fig. 8)

Once mounted to the mast at the correct height, the probes were individually aligned by eye so that the *x*-axes of the probes were nominally horizontal and perpendicular to the mast cross-head. The set of probes were then aligned to the time averaged wind direction initially by aligning the attitude to match a streamer attached to the mast. To better align the probes short data samples were recorded and the probes adjusted accordingly. This ensured that all wind vectors would be contained within the $\pm 45^\circ$ cone of acceptance. Three inter-probe separations of 0.014m, 0.05m and 0.15m were used giving possible spans of 0.042m, 0.15m and 0.45 m. It was assumed in the analysis that the time averaged wind direction for all probes over the sampling time (60 seconds) are equal. In doing this the necessity of aligning probes exactly is eliminated as this can be done in post processing via adjusting the results such that the mean pitch and yaw angles are the same for all four probes.

Wind speeds during the testing period ranged from 3ms^{-1} to 7ms^{-1} and only tests with a mean wind speed of over 5ms^{-1} have been used. As the probes are a pressure based device, records with mean velocities lower than this were deemed to be too inaccurate. Hardware limitations of the recording equipment dictated that the probes could be sampled at a maximum of 767.8Hz; multiple data sets of approximately 60 seconds duration were recorded for each of the three inter-probe spacings. It should be noted that wind engineers and meteorologists usually employ data sample lengths of typically 1 hour; however a shorter sampling time can be used here as the frequencies of interest are much higher. The lowest frequency of interest here is 0.1Hz (see later). The turbulence intensity of the flow ranged from 10% to 20%. As was expected, there appeared to be no relationship between mean velocity and turbulence intensity.

A small correction was applied for data recorded with probes laterally separated by 0.014m to account for the blockage created below the probes by the probe bodies (see Fig. 5). The correction was determined via a series of wind-tunnel tests comparing the data recorded by a single probe in isolation to those recorded by the four probes fixed on the mount with the probes set at a range of angles in relatively smooth flow (a wind-tunnel with 0.75% turbulence intensity) and confirmed in a wind engineering wind tunnel with 7% turbulence intensity. Correction factors were found to be negligible for inter-probe spacings of 0.05m and 0.15 m.

As is commonly found with atmospheric velocity measurements, low frequency events are evident in the raw data. These events can detrimentally influence the results. Therefore the relatively slow fluctuations, which can be considered to be quasi-static, have been removed via a high-pass 2nd order Butterworth filter at 0.1Hz before further analysis⁽⁹⁾.

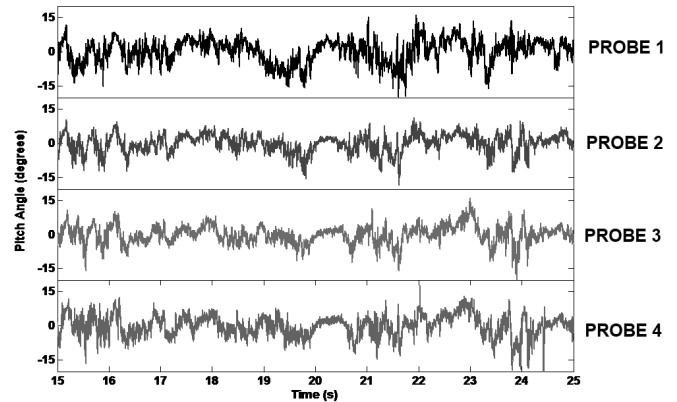


Figure 11. Pitch angle of four probes over 10s (0.15m interprobe spacing).

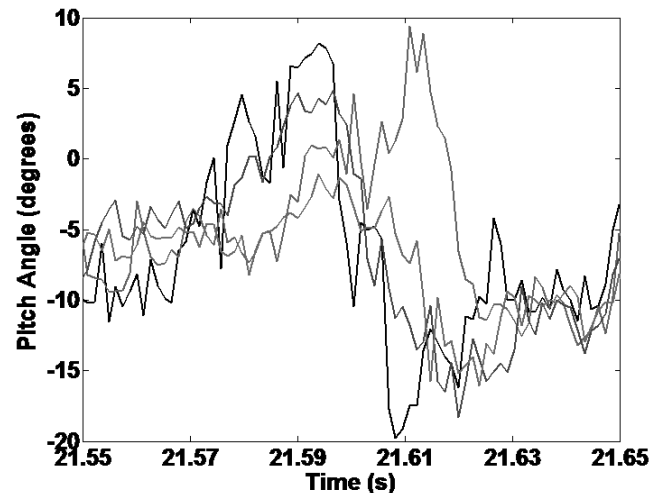


Figure 12. Pitch angle of four probes over 0.1s (0.15m interprobe spacing).

3.0 RESULTS AND DISCUSSION

3.1 Longitudinal velocity and pitch differences

From Equation (1), the standard equation of lift for an aerofoil, the only variables that relate to atmospheric gusts (excluding the air density of which variance is negligible) are flow velocity and the coefficient of lift, which in turn depends on the relative pitch angle of the flow. The following presentation and discussion of results focuses on these two variables,

$$L = C_L \cdot \frac{1}{2} \rho V^2 S \quad \dots (1)$$

A 10 second extract of the longitudinal velocity from the four probes with lateral separation of 0.15m is shown below in Fig. 9. The mean wind speed for this test was 4.5ms^{-1} and the turbulence intensity was 18%. It is immediately apparent that the longitudinal component of the velocity varies significantly between 3.5ms^{-1} and 6ms^{-1} over the 10 seconds; however all four plots appear to be reasonably well correlated. Selecting a shorter time span of 0.1 seconds (see Fig. 10)

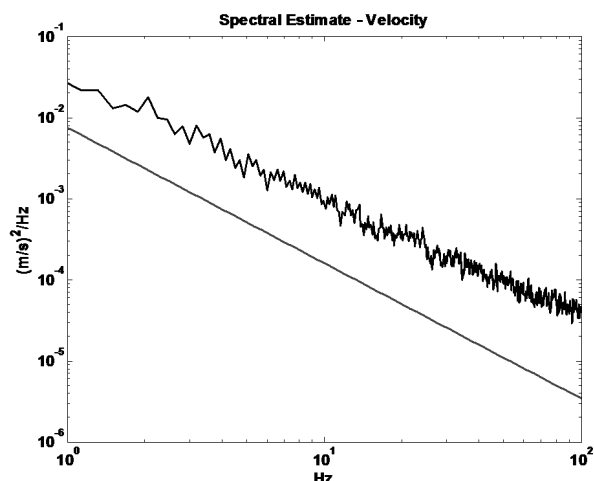


Figure 13. Spectral plot of velocity vector (with $-5/3$ Kolmogorov theoretical slope for comparison).

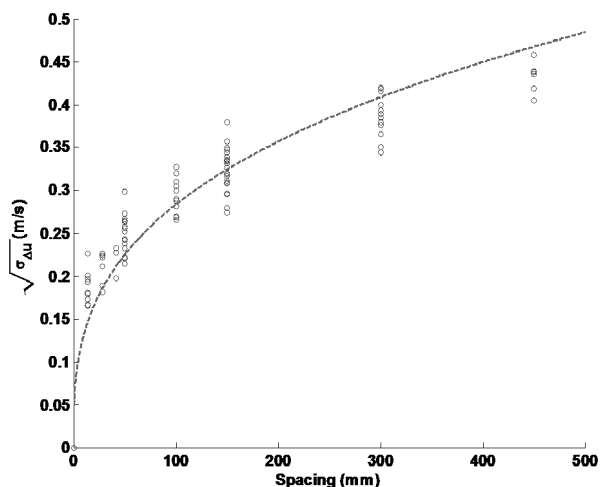


Figure 14. Longitudinal velocity structure function.

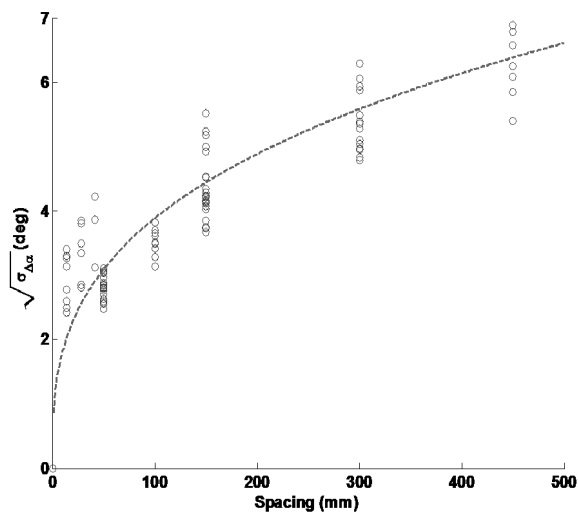


Figure 15. Pitch angle structure function.

reveals that there are indeed large differences between the measurements of the four probes, in this case as much as 2.5ms^{-1} between two probes that were separated by 0.15m .

Using the same approach and time series as for the longitudinal velocity analysis it can be seen that the pitch angle behaviour is similar, (see Figs 11 and 12). Overall the pitch angle appears relatively well correlated for all four probes over a long time sample (see Fig. 11) however examining a much shorter time reveals that instantaneous differences between laterally separated probes can be very large, up to 30 degrees (see Fig. 12). Fig. 11 shows a typical spectrum of the energy versus frequency content in the velocity measurements from a single probe, as expected it indicates a $-5/3$ decay.

To obtain a measure of the magnitude of the differences between instantaneous flow measurements, the standard deviations of differences between probe measurements were calculated. This calculation is a variation on the structure function, using the standard deviation in place of the variance. This produces 6 values for each data set as pictured in Fig. 7, those being the differences between probes 1-2, 2-3 and 3-4 at the inter-probe spacing, 1-3 and 2-4 at twice the probe spacing and 1-4 at three times the inter-probe spacing. This was done for both the longitudinal velocity and the pitch angle. The results roughly followed a power law trend for increasing inter-probe spacing. The scatter is believed to be a result of continually changing atmospheric conditions such as flow velocity, turbulence intensity, temperature etc. The combined results from all data sets are presented in Figs 14 and 15.

The theoretical relationship between the structure function and data separation⁽¹²⁾ in the sub-inertial range of turbulence is a $1/3$ power law (taking into account the standard deviation has been used here instead of the variance). On each of the plots a dashed red line provides a power curve of best fit where the power term has been forced to $1/3$. As can be seen the measured data fits well with the theoretical curve although some scatter is present. This indicates that over the range of separations tested, the turbulence is contained within the sub-inertial range of turbulence.

It should be noted that there are an infinite combination of directions and speeds at which an aircraft can fly through the atmosphere. Thus far the only possibility covered has been for the aircraft stationary with respect to the ground (i.e. the aircraft speed through the air is equal to the mean wind speed since the data were acquired on a fixed mast). The data acquired here can be used in a number of ways by modifying the mean u , v and w component velocities to replicate different simulated flight speeds and directions of an MAV. This leads to a wide variety of potential wind environments. Only the simplest option of adding a constant u component velocity to the data, simulating an aircraft flying into or with the wind is considered here.

At wind speeds below 10ms^{-1} thermal stratification in the ABL can have a significant effect on the lower frequencies of the turbulent structure of wind. No measurements of the thermal stability in the area were made, however it is estimated that neutral or slightly unstable conditions were present. From results presented by Kaimal and Finnigan⁽²¹⁾ there is no discernable effect on the frequency spectra at the frequencies of interest here ($< 0.1\text{Hz}$) for these stability conditions. Thus it can be concluded that the thermal effects in the data should be negligible and similar results would be obtained for all winds speeds of interest to MAVs provided the turbulent structure is generated in the same manner, i.e. by mechanical mixing over a similar terrain.

Flying through turbulence will have no effect on the standard deviation of velocity, or the standard deviation of the velocity difference between laterally separated points in space. For pitch angles however there will be a change. Generally increasing the flight speed reduces the fluctuating pitch angles of the flow with respect to the aircraft. As the flight speed relative to the air approaches zero the relative turbulence intensities asymptote to infinity.

3.1 Effect of differences on lift production across virtual spans

With the above results it is difficult to visualise and compare the effect that the fluctuating u and w component velocities will have on the lift (and hence roll) experienced by an aerofoil in the flow. By using the recorded velocity and pitch angle to calculate potential lift forces, the results are more easily associated with an aircraft flying in the wind. Consider a two dimensional aerofoil section, stationary with respect to the ground, subjected to the velocity and pitch angle of the wind as depicted in Fig. 16(a). The potential lift (albeit for a wing with an infinitely small wing chord such that the transfer function of the wing is equal to one at all frequencies) can be calculated using Equation (2), (note that the equation calculates lift per unit area) where the recorded velocity magnitude and pitch angle can be used for the terms V and α respectively. The results are presented in non-dimensional form by dividing the lift per unit area by the mean dynamic pressure (Equation (3)).

$$\frac{L}{S} = 2\pi\alpha \cdot \frac{1}{2}\rho V^2 \quad \dots (2)$$

Using

$$C_L = \frac{L}{\frac{1}{2}\rho \bar{V}^2 S} = 2\pi\alpha \frac{V^2}{\bar{V}^2} \quad \dots (3)$$

Note that this analysis is very similar to applying a simple strip theory model⁽²²⁾. Therefore is subject to the same limitations; a steady state condition for each calculation (or alternatively the lift force can be thought to act instantaneously such as on an infinitely small aerofoil chord), the lift curve slope is taken to be a linear function for all pitch angles (stall is not considered) and there is no consideration of the 3D effects of either the turbulence or the aerofoil interaction with the air.

Consider now four two dimensional aerofoils spaced equally along a span (see Fig. 16(b)) subjected to the velocity field measured by the four probes. The same analysis can be applied for all four probes with a different set of data for each aerofoil. Instead of four pitch angles and four velocities, there are now simply four lift forces to compare.

In order to compare the fluctuating velocity and the fluctuating pitch angle, the analysis is performed in two parts. First a constant pitch angle is used with the fluctuating velocities and secondly a constant velocity is used with the fluctuating pitch angles. To allow different sets of velocity measurements to be compared, a unique angle of attack α_r is added to each set of data such that the mean lift per unit area produced by each set of velocities is equal to 1N/m² (Equation (4)), in effect ‘trimming’ the airfoil for a constant mean lift across all data sets. 1N/m² is a typical wing loading of nature’s lighter MAVs, such as butterflies⁽²³⁾ and while current generation MAVs have wing loading somewhat higher than this, as research and development continues the wing loading is expected to reduce to this value. A low wing loading will increase the susceptibility of an aircraft to turbulence, hence the use of this value.

$$\frac{\bar{L}}{S} = \frac{1}{n} \sum_{i=1}^n \left[\frac{1}{2}\rho V_i^2 \cdot 2\pi(\alpha_i + \alpha_r) \right] = 1 \quad \dots (4)$$

As it is potential roll inputs that are of most interest here the structure function of the lift coefficient fluctuations is calculated using the same method as used previously in this paper whereby the standard deviation of the difference between the instantaneous lift coefficients at two points is determined. The results are presented below in Fig. 17 and Fig. 18. In Fig. 17 the results are plotted for the case of the fluctuating pitch angle with a constant mean velocity and in Fig. 18 the results of using a fluctuating velocity with a constant angle of attack are shown.

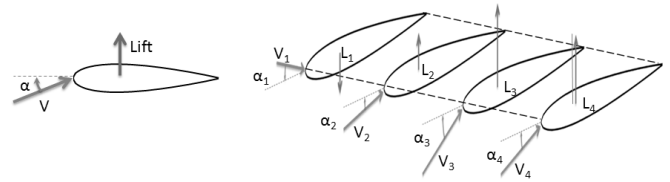


Figure 16 a.) Single probe data used to calculate lift and b.) Four probe data used to calculate lift.

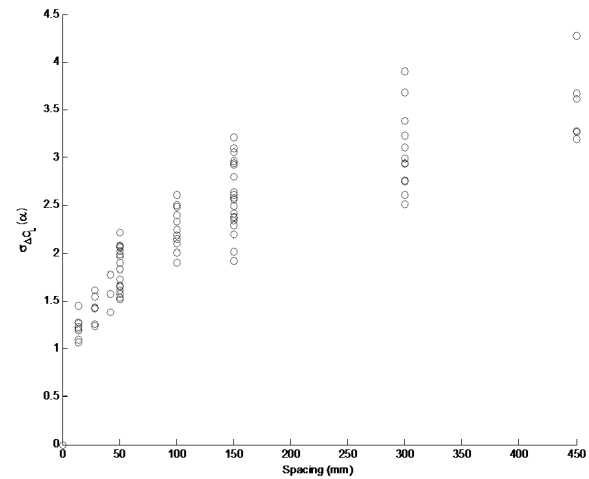


Figure 17. Lift coefficient structure function (using fluctuating pitch angle).

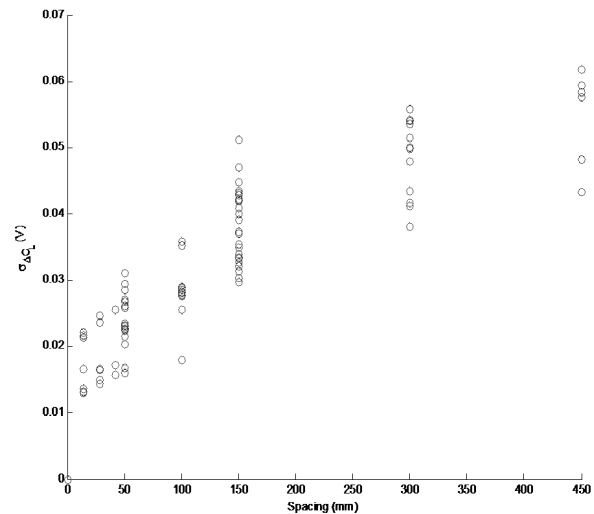


Figure 18. Lift coefficient structure function (using fluctuating velocity).

Comparing the lift coefficient structure function plots it is clear that the pitch angle fluctuations are significantly greater than the velocity fluctuations. For a lift curve slope of 2π , fluctuations in pitch angle cause lift force deviations in the order of 50 to 100 times that of velocity magnitude fluctuations. It should be noted that the values calculated with fluctuating pitch angle are directly proportional to the lift curve slope. Using a more realistic lift curve slope for a low aspect ratio wing of 2.9α , as presented by Torres and Mueller⁽²⁴⁾, the magnitude of the difference between the influence of

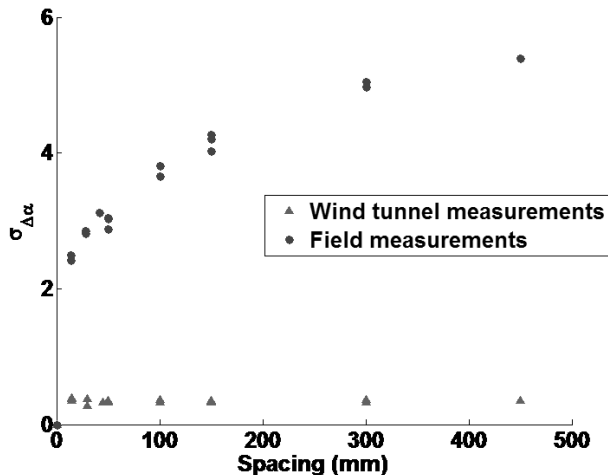


Figure 19. wind-tunnel data (red triangle) plotted with selected field data (blue circle).

the pitch angle and the velocity fluctuations reduces by a factor of $2\pi/2.9$, to between 25 to 50.

The assumed flight speed of an MAV travelling through this turbulence does have an effect on these values, increasing the flight speed will reduce the effects of turbulence. A flight speed of zero with respect to the ground has been assumed as it provides a good compromise between the most challenging conditions (very low flight speed) and the most probable flight speed ($5\text{--}10\text{ms}^{-1}$ air speed). Changing the flight speed does have an effect on the magnitude on the lift difference resulting from either velocity fluctuations or pitch angle fluctuations although by differing amounts. With an increasing vehicle flight speed the lift difference from pitch angle fluctuations becomes more significant than velocity fluctuations.

3.2 Error considerations

Due to the nature of the measurements (i.e. examining the differences of small angles and velocities) careful consideration of the errors associated with the acquisition system is necessary. These include the data acquisition errors (resolution, sampling frequency, inter-channel delay etc.) which have been analysed extensively by Pagliarella⁽²⁵⁾ and has been shown to be up to $\pm 0.1^\circ$. Other errors, such as those arising from differences in probe tip positions (including those due to vibrations) were investigated in two auxiliary experiments. These were performed in a wind engineering wind-tunnel (turbulence intensity, 7%) as well as in a relatively smooth-flow wind-tunnel (turbulence intensity, 0.75%). The same supporting mast, structure etc. were used and data were analysed in the same fashion as that recorded in the field experiment. In the latter, the velocity fluctuations (including the pitch angle variations) are very small and any pitch angle fluctuations would be from a combination of the low level of turbulence in the tunnel and from errors in the system. Typical results are plotted in Fig. 19; the blue circles are a selection of the data from the field tests and the red triangles are the data from the smooth flow wind-tunnel. As can be seen, the data from the tunnel are well below that recorded in the field giving confidence in the field test data.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Dynamic wind gust measurements recorded by four laterally separated probes have been presented. The measurements have

allowed quantitative analysis of structure of atmospheric gusts at spatial and temporal resolutions that are applicable to MAVs and small natural fliers. By calculating the lateral structure functions of the velocity magnitude and pitch angle differences versus spacing, it was found that both relationships follow the theoretical $1/3$ power law for sub-inertial turbulence. This may be of interest to those simulating atmospheric turbulence as it suggests that in the frequency range of interest the turbulence is locally isotropic.

Using the velocity and pitch angle dynamic data to calculate the lift that would be produced by two dimensional strip theory it was found that the pitch angle variations have a much greater effect than velocity fluctuations although the amount depends on the lift curve slope used. The results give an indication of challenge MAVs face when operating in real world environment.

Following the work presented here a number of recommendations can be made to further the knowledge in the area.

- Record and analyse data in a similar manner from areas with increasingly complex terrain.
- Further the analysis to calculate the potential rolling moments, rolling accelerations and rates that an aircraft would experience in real world conditions.
- Incorporate the use a transfer function such as the Sears Function⁽²⁾ to further investigate the effect on lift production and take into account the response in the frequency domain of an aerofoil.

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