Small scale flight within the lower regions atmospheric boundary layer

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1 INTRODUCTION

As man-made flight developed the power and technology to fly above the Atmospheric Boundary Layer (ABL) and the high levels of turbulence within it, atmospheric research in aerospace and wind engineering have been separate ventures. Today there is a new breed of aircraft in development that will fly only within the lower ABL, the Micro Aerial Vehicle (MAV), and with it aerospace research is beginning to make use of and augment data that has been collected by wind engineers and meteorologists.

MAVs are extremely small (up to 30cm wing span), light (up to 100 grams) aircraft that operate at low Reynolds numbers (10^3 - 10^5) [1] with the primary envisaged mission being surveillance and therefore will require excellent control in roll and pitch so as to provide a stable platform for video recording. In the design and flight of the first generation of these aircraft the lack of knowledge about the ABL as a flight domain and the effect of this on flight performance were evident from the poor performance of the aircraft particularly in being able to hold straight and level flight. A typical MAV is shown in Fig. 1.

It is important then that the wind environment be understood and taken into account when designing MAVs if they are to be useful over a high number of days per year - not just when the wind gusts are insignificant. Data from resources such as the ESDU data sheets [2] have been valuable in providing single point data for a range of locations however data from multipoint simultaneous measurements are less common and those available are of little use as their spatial and temporal scales are significantly greater than those of interest for an MAV.

Here multipoint measurements taken at a height of 2 meters and covering spans of lateral separation 15mm to 450mm in "Open" terrain are presented. While this is the least complex terrain type expected for MAV flight, it 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.

Fig. 1 - A typical MAV

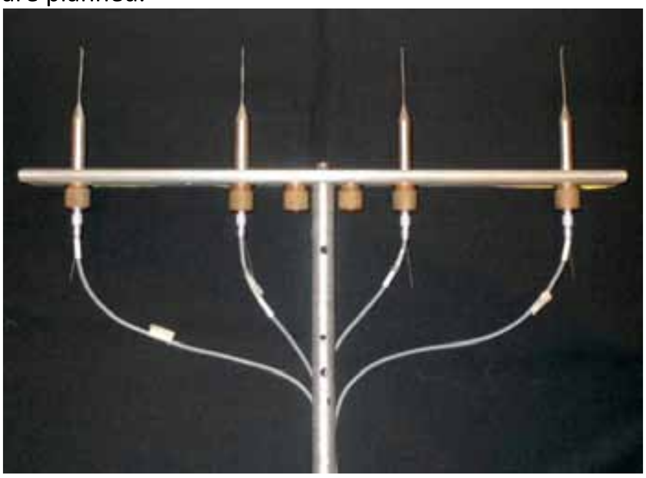

Fig. 2 – 4 Cobra probes spaced at 150mm on mast

2 EXPERIMENTAL PROCEDURE

The results presented here were recorded in the Lliw Valley in Southern Wales. The test location was near the top of a slight rise surrounded by slightly undulating terrain. The fetch for over 1km upwind of the probes was open grassland.

Four four-hole pressure probes, known as TFI Cobra Probes [3], of 2.6mm head dimension were mounted on a lateral cross-head (see Fig. 2). 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. Multi-hole probes were used because they provide a more robust alternative to hot-wire anemometers and, via a dynamic calibration, have a frequency response that is flat to over 2 kHz. 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 ±45° around the probe x-axis. Details of the system and examples of use can be found in [4] and verification and further details including dynamic capabilities, probe operation methodology and calibration techniques can be found in [5] and [6].

Three inter-probe separations of 14mm, 50mm and 150mm were used giving possible end to end spans of 42mm, 150mm and 450mm. We make an assumption in this 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 across all 4 probes.

Wind speeds during the testing period ranged from 5m/s to 7m/s. 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. Turbulence intensities throughout the testing period ranged between 10-20%. Relatively slow fluctuations with a period of more than 10 characteristic lengths can be considered to be quasi-static and have been removed via a high-pass 2nd order Butterworth filter at 0.1Hz.

3 RESULTS AND DISCUSSION

The instantaneous lift force is dependent upon the 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 variables.

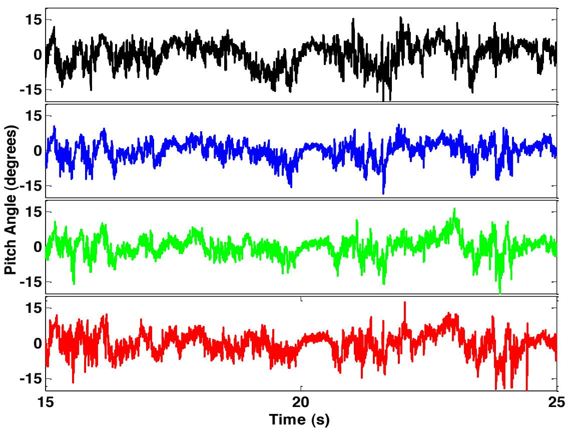

Fig. 3 - Pitch angle of 4 probes over 10s

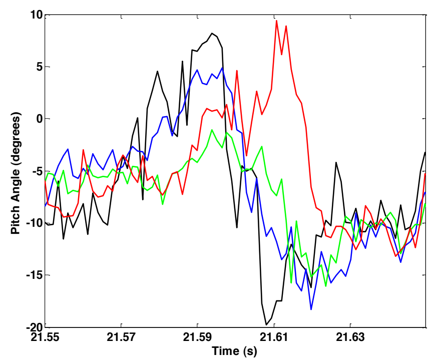

Fig. 4 - Pitch angle of 4 probes over 0.1s

A 10 second extract of the pitch angle fluctuations from the 4 probes with lateral separation of 150mm is shown above in Fig. 3. The mean wind speed for this test was 5m/s and the turbulence intensity, 18%. It is immediately apparent that the pitch angle varies significantly between -20 and +20 degrees over the 10 seconds; however all 4 plots appear to be reasonably well correlated. Zooming in further on the time axis to a 0.1 second span (Fig. 4) reveals that there are indeed large differences between the measurements of the 4 probes, in this case as much as 30 degrees between two probes that for this case were separated by 150mm. Similar behaviour is seen in the velocity fluctuations with recorded differences between probes of up to 2.5m/s

To obtain a measure of the magnitude of the differences between instantaneous flow measurements, the standard deviations of differences between probe measurements were calculated. The results roughly followed a fractional power law trend for increasing 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 Fig. 5 and Fig. 6 with a power law curve of best fit applied to both sets of data. It should be noted that these plots are very similar to structure functions [7], only differing in that they plot the standard deviation instead of the variance.

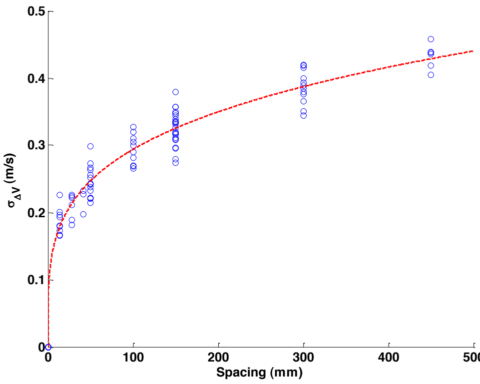

Fig. 5 - Velocity variation with spacing

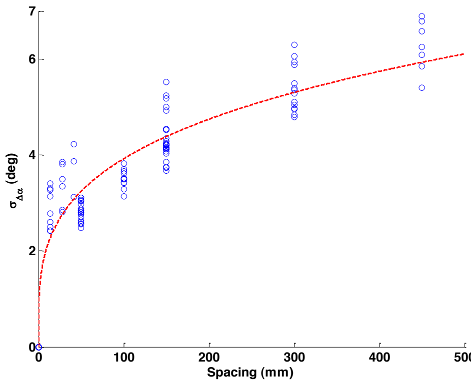

Fig. 6 - Pitch angle variation with spacing

To make these results more relevant to flight the measurements were analysed in the form of fluctuating lift forces. Consider a stationary (with respect to the ground) 2-dimensional aero foil section subjected to wind velocities and directions as measured by one of the probes (Fig. 7). Now using the lift equation in the form of lift per unit area and a simple theoretical lift curve slope the velocity and pitch angle recorded by a probe can be used to calculate the lift per unit area an aero foil would produce in such conditions. The same procedure can be applied for all four probes with a different set of data for each aero foil (Fig. 8).

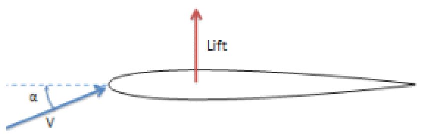

Fig. 7 - Single probe data used to calculate lift

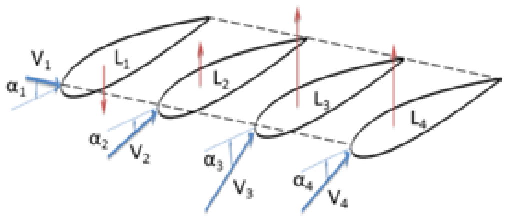

Fig. 8 - 4 probe data used to calculate lift

Using this method the effect of velocity fluctuations could be studied by taking a constant pitch angle and using the velocity data as recorded as well as the pitch angle fluctuations by taking a constant velocity and using the recorded pitch angle data. After calculating the lift force time histories the same process as in the previous section was applied in which the standard deviations of the differences between probes were calculated and plotted as a function of measurement spacing. The results are plotted in Fig. 9 and Fig. 10. In this form cross comparison of the effects of pitch and velocity fluctuations is possible. The pitch angle fluctuations are more significant than the velocity fluctuations. For a lift curve slope of 2πα, fluctuations in pitch angle cause lift force deviations in the order of 50 to 60 times that of longitudinal velocity fluctuations. It should be noted that the values calculated with fluctuating pitch 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 & Mueller [8], the magnitude difference between the pitch angle and the velocity fluctuations reduces by a factor of (2π/2.9) to roughly 25- 30 times.

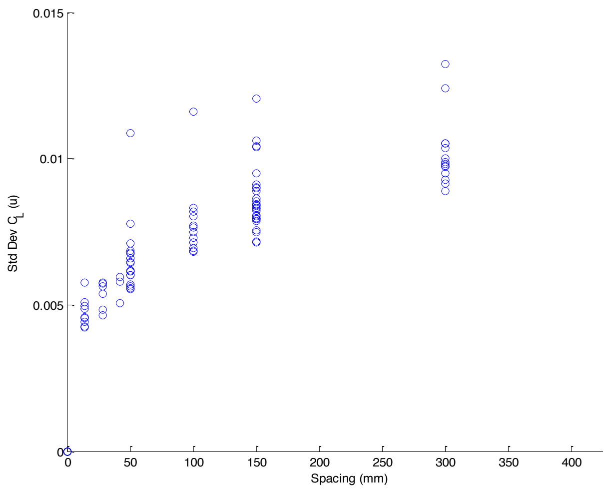

Fig. 9 –ΔLift vs spacing from varying velocity

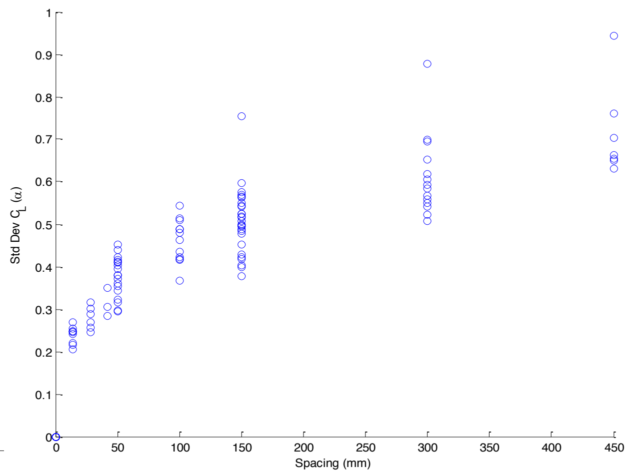

Fig. 10 – ΔLift vs spacing from varying pitch angle

4 CONCLUSIONS

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. Using the velocity and pitch angle dynamic data to calculate the lift that would be produced by 2D 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 highlight the challenging nature of the flow environment, particularly for small span craft flying through the atmospheric boundary layer.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

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