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Atmospheric Winds and Their Implications for Microair Vehicles

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Major challenges to low speed microflight are the transient and time-averaged velocities arising from the atmospheric boundary layer, particularly turbulence a few meters above the ground. In this paper, prior work on the temporal and spatial characteristics of the atmospheric boundary layer close to the ground, and the relative turbulence as perceived by a moving craft, are considered. New measurements are described that document the time-averaged and transient velocities at a height of 4 m above the ground. These were made using a bank of four multihole pressure probes laterally separated by 150 and 50 mm on a mast above a test car. Transient flow pitch angles were investigated and it was found that the overall variation with lateral separation decreased relatively slowly with reducing separation, but that both this and the pitch angle coherence may be described nondimensionally. As the slow decrease in pitch variation with lateral spacing implies that the roll inputs arising from vertical fluctuations would increase with reducing span, it is speculated that increasingly active and authoritative control systems are required.

Nomenclature

C_{ij}	=	coherence in pitch angle between points i and j [$=\lvert S_{ij}\rvert^2/(S_{ii}S_{jj})$]
d	=	lateral distance between measurement points
f	=	frequency
I	=	turbulence intensity of the ambient wind
J	=	turbulence intensity perceived by a moving object
k	=	wave number ($=f/V_r$)
L	=	integral length scale of the flow
S_{ij}	=	power spectral density between data at points i and j, calculated using no data window and averaging using 50% overlap (Bartlett's modified periodogram technique)
T	=	measurement sample length
t	=	time
u, v, w	=	ambient wind velocity components in the x, y, and z directions, respectively (where $u=\bar{u}+u'$)
V_r	=	overall relative velocity magnitude
V_{veh}	=	vehicle velocity magnitude
V_w	=	ambient wind speed
α	=	pitch angle (angle of attack) [$=\tan^{-1}(w/u)$]
$\Delta\alpha_{ij}$	=	pitch variation, or the difference in pitch angle between points i and j
σ	=	standard deviation
$\sigma_{\Delta\alpha}$	=	pitch variation fluctuation
Ψ	=	yaw angle [$=\tan^{-1}(v/u)$]
$\bar{\ }$	=	indicates a time-averaged or mean component
$'$	=	indicates a fluctuating component (i.e., the mean component has been removed from the variable)

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I. Introduction and Aims

THE natural world and the human constructed environment are significantly influenced by the atmospheric boundary layer (ABL). The ABL is the region of the atmosphere that is influenced by the frictional effect of the surface of the Earth and extends from the ground surface to between 100 and 1000 m, 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 considerable 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. Under relatively low wind speeds the smaller flying insects remain grounded, and as the wind speed rises, increasingly larger insects, then birds, become grounded. This is despite having extremely sophisticated, interactive, control systems. A summary of flying speeds is reproduced from [1] (Fig. 1) indicating the wind conditions that different animals and aircraft can fly in.

Military and the larger commercial aircraft can generally fly in all but the most extreme wind conditions (e.g., cyclonic), but as the size and mass of the aircraft reduce, the ability to maintain control and satisfactory forward motion reduces for any given wind condition. Much work has been done on understanding the turbulence inherent in atmospheric winds and its effects on the response of structures and aircraft; see, for example, [2,3]. It is now common practice to provide correctly scaled models of atmospheric turbulence when undertaking both time-averaged and time-varying studies on buildings, masts, bridges, and other stationary structures, yet this is generally not done on aircraft.

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 [4,5]. A recent Defense Advanced Research Projects Agency (DARPA) specification supporting research programs into microair vehicles (MAVs) [6], has

Wind Speed, m/s	Beaufort Wind Scale Force	Description	
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	

Fig. 1 The flying speeds of birds and insects from Tennekes [1].

led to many small craft being evaluated. These craft are characterized by their small dimensions (the initial DARPA specification was for them to be "bounded" by a 150 mm box, although this DARPA specification has since been revised to "manportable"), light weight (~65 g), and a relatively short flying duration (20 to 40 min). Examples of such craft can be found in [7–9]. Ongoing research into insect aerodynamics [10] has also been utilized to assist in the efforts in miniaturization and controllability, such as a robotic fly demonstrator of 1 in. wingspan [11] developed by R. Fearing and M. Dickinson at the University of California Berkeley[‖] and ongoing research into insect flight dynamics and simulation by several researchers [12], including R. Zbikowski at Cranfield University in the United Kingdom.[¶]

Because of the missions envisaged for MAVs of short-range reconnaissance and surveillance, and the operational environment dictated by terrain and weather [13–15], 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 that for larger aircraft that cruise above the ABL.

Consequently, the environment is emerging as a major constraint on the operations of MAVs, with an increasing vulnerability to turbulence as size and speed reduces [16]. Flexible wings might alleviate some of the effects of turbulence, but small wind gusts have extremely deleterious effects on such small craft. Investigations of the controllability of MAVs, including an MAV of 4.5 in. span, have been made by [17] who analyzed flight control positions via reversal counting and autospectra in order to determine the best aircraft under a range of atmospheric conditions. It was concluded that control "workload" was unquestionably related to how often rapid (1 to 10 Hz) control movements must be made to maintain stability.

The most common role for RPVs is one of surveillance, using very low mass video and other forms of observation (see [8] for information on 4 g video camera and telemetry instrumentation). As well as the problems associated with flight under turbulent winds, holding a stable viewing platform becomes increasingly difficult as aircraft scale reduces. In particular roll, pitch and (to a lesser extent) yaw motions have a significant influence on image sharpness, whereas the influence of vertical, lateral and fore and aft translations are minimal.

There are now several MAVs that have demonstrated outdoor flight, including that reported in [18]. 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 with respect to MAVs, as well as the effects of 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.

Little work has been done on understanding the wind environment of relatively slow flying craft close to the ground. This is in stark contrast to the aerodynamic testing of land-based structures where testing in correctly scaled atmospheric boundary layers is commonplace. There is a substantial database of wind data, generally gathered from masts at heights of 10 m or greater for wind engineering uses.

To provide information on the roll and pitch disturbances encountered close to the ground for small aircraft, multipoint measurements of the velocity field are needed, including documentation of fluctuations up to the maximum frequencies of interest. Ideally a simultaneous series of measurement made at points representing the path of the aircraft through a variety of atmospheric conditions (including varying winds and "city canyon" terrains) would enable a further understanding of the disturbances.

The aims of this paper are to review the existing database of measurements close to ground level from fixed and moving perspectives and to present recent results of measurements taken from velocity probes fixed to a mast above a stationary and moving vehicle.

II. Existing Body of Knowledge

A. Atmospheric Data: Historical Perspective, Current Knowledge, and Relevance

The ABL extends from the ground up to a height of several hundred meters. It has been studied over much of the previous century and the spatial and temporal variations of the wind (with location and height) have been documented by many workers. Information was obtained by wind engineers using relatively large anemometers on fixed masts at heights well removed from the ground (in order to predict loadings on masts, tall buildings, etc.) [2,19–22].

The variation of mean wind speed with height for locations around the world is well documented and the mean speeds can be such that forward motion of some slower flying MAVs would not be possible for some of the time. However, the aim of the current review and associated work is to investigate the turbulence or fluctuating properties in the ABL, when mean flow speeds are otherwise within a suitable range for flying.

The Engineering Sciences Data Unit (ESDU) data sheet 74030 [23] provides summaries of atmospheric data up to 1974 and ESDU 85020 [24] revises and summarizes single-point data to 1985. A third data sheet, ESDU 86010 [25] details the variations in atmospheric turbulence in space and time for strong winds. Some multipoint data sets exist (obtained simultaneously from several anemometers displaced vertically or horizontally); however, because it is well known that the turbulence in the ABL varies strongly as a function of height from the ground (and that most wind-sensitive structures are slender in the vertical sense) the spatial separation is usually in the

[‖]See http://robotics.eecs.berkeley.edu/%7Eronf/MFI/index.html [cited 18 January 2006].

[¶]See http://www.rmcs.cranfield.ac.uk/daps/guidance/microairvehicles/view [cited 18 January 2006].

vertical sense. From such measurements it is known that with increasing closeness to the ground the turbulence intensity increases and changes characteristics. Above the ABL the air is relatively smooth. (At heights relevant to commercial and military aircraft operations there can be "clear air turbulence" and turbulence due to convection, but this is not relevant here.) Under all but very low wind speeds (less than about 3 m/s) or in storm conditions the turbulence in the ABL is generated by mechanical mixing, resulting from the wakes of objects on the ground. As the ground surface is approached the vertical fluctuations are attenuated, thus turbulent energy is mainly in the horizontal plane. However, there can still be significant energy in the vertical direction in the last few meters.

Traditionally wind data are usually obtained utilizing propeller, cup, dynes, or ultrasonic anemometers that are placed either in isolation or located on vertical masts with interanemometer spacing of several meters. This reflects the interest of the building and road vehicle aerodynamics communities where the structures or vehicles are relatively large in relation to the turbulence scale. Data with the closest anemometer spacing appear to be the work of [26], with a spacing of ~2.2 m, which was subsequently included in ESDU 85020 [24]. The size and mass of the individual anemometers used was similar to the size of MAVs (in common with nearly all meteorological surveys), thus they cannot provide the spatial or temporal resolution needed to discriminate the turbulence characteristics relevant to MAVs. In common with meteorological measurements they were located in a vertical arrangement to primarily provide information as a function of distance from the ground surface.

Two point simultaneous measurements in the horizontal plane have been made in order to provide direct measurement on the spatial structure of turbulence [27] and some hot-wire measurements have been reported by [28]. These studies were taken over grass or forest canopies to further the understanding of turbulence and its effects on vegetation. To provide enhanced spatial (and frequency) resolution, some single-point measurements have also been undertaken using hot-wire anemometry (HWA) for vehicle aerodynamics studies and these are discussed in more detail in the next section.

And so, despite a large database of wind engineering information on the characteristics of the ABL documented over a period of more than 100 years, the majority of that data are mainly relevant to structures orders of magnitude larger than MAVs. Thus the spatial and temporal resolution of this data is not fine enough for MAV scales and the principal axis of investigation of the existing data (i.e., the vertical axis) is perpendicular to that required for MAVs.

B. Turbulence Environment Experienced by Moving Vehicles

The relative air velocity (defined here as the velocity experienced by the moving vehicle) is the vector sum of the velocity of the atmospheric wind and the vehicle velocity relative to the ground. (Note that the axes system used is defined relative to the vehicle or moving object (effectively an aircraft body axis system) and originates from ground vehicle aerodynamics. Such an axis system affects calculation of perceived turbulence intensities and flow angles, as will be discussed later.) Analytical frameworks that relate the turbulence characteristics for a single point on moving road vehicles to characteristics obtained from ground-based anemometers have been developed by [29–32].

To provide enhanced spatial and frequency resolution, some single-point measurements have been undertaken using HWA from masts above stationary and moving vehicles; see for example the work of [33]. (HWA permits a resolving dimension of ~3 mm, but as such sensors rely on very fine heated metal wires, they are extremely fragile and change calibration with temperature. When operated outside the laboratory environment, they are troublesome and thus not generally suited to measurements of atmospheric turbulence.) For vehicles moving at 100 km/h through atmospheric winds of between 1 to 9 m/s the measured longitudinal and lateral turbulence intensities on the moving vehicle were in the range 2.5 to 5% and 2 to 10%, respectively. Spectra obtained from the moving vehicle were shown to have peak energy at about 1 Hz although it varied between about 0.25 to 2.5 Hz. This work and the effects of the turbulence field on parameters of interest to passenger vehicles have been communicated in [34], and reviewed in [35].

Although the height above the ground at which vehicle measurements have been taken is more relevant to MAV flight, and the work of [33] encompassed a reasonable frequency response and spatial resolution due to the use of HWA, measurements are still mostly single-point and do not document the turbulence spatial correlation at multiple points.

To define relevant atmospheric parameters for MAV flight through the ABL, identical techniques to those used with road vehicles may be used for multipoint measurements, but the MAV velocities are significantly lower and the difficulties of using hot-wire anemometry for a significant multipoint study in atmospheric conditions are problematic. As MAV velocities are lower than automotive velocities, expected operational turbulence levels experienced by MAVs will generally be larger than that experienced by automotive vehicles and peak frequencies will be lower (due to the body axis system used). (Using a body axis system results in variations in perceived turbulence intensity magnitude due to mean vehicle speed. However, these turbulence levels are those experienced by the aircraft/vehicle during flight, and therefore those that any control strategies will have to cope with.) However, MAV control characteristics also mean that peak frequencies are not the sole parameter of interest but energy levels over a defined frequency range are important.

C. Multipoint Measurements

Two or more velocity measurements removed by a vertical or horizontal separation enable the variation of loads with location to be predicted for structures or vehicles. This variation in loads can lead to a reduction in the dynamic loading because peak loads at points distributed over the structure generally do not occur at the same time, that is, they are not correlated. Reflecting the interest of the wind engineering community, measurements (in either the along, cross, or vertical wind direction) are usually separated in the vertical plane. However, for the purposes of understanding the roll and pitch inputs for aircraft, vertical velocity fluctuations separated in the horizontal plane (separation distances of characteristic aircraft dimensions such as span, or semispan seem most relevant) are required. Such data close to the ground are rare. A summary of reliable atmospheric measurements to 1983 is given in [25]. Data on vertical velocity fluctuations separated in the horizontal plane are given by [36–38]. All works present data obtained over very smooth terrains ("coastal waters, open country, and snow-covered rolling terrain" and "open terrain") at heights of 11 m or more, with lateral separations of several meters that are many times the span of MAVs.

A useful and interesting depiction of atmospheric turbulence very close to the ground is given in Fig. 2 (note the person standing in the left-hand side for an indication of scale). Although surface tension effects minimize the influence of the extremely small structures in the atmosphere, distortion of the soap film depicts some of the small to medium scale structures in the first few meters of the ABL that influence microflight. The influence of various scale eddies are apparent, ranging from less than half a meter to approximately 15 m (the total length of the bubble is 32 m). Less evident, but arguably more significant to the flight of MAVs, is vorticity about a horizontal axis which is apparent one-third of the way along the length of the bubble and toward the end.

To document the relevant flow characteristics illustrated above, several requirements must be met: the instrumentation used must be of a size and have capabilities appropriate to achieve the required spatial and temporal resolution for MAV flight; instrumentation separation should be in the horizontal plane; and measurements should be taken at appropriate overall relative velocities, height above the ground, and also in relevant terrains for MAV operational requirements.

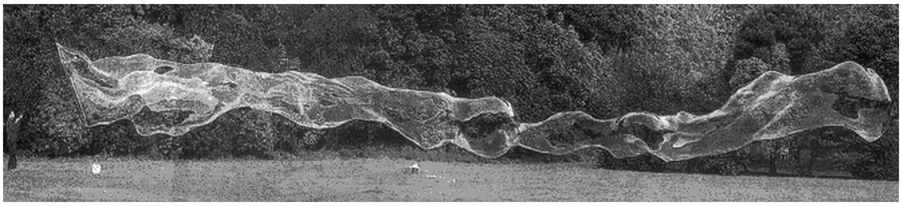

Fig. 2 The longest bubble in the world, 1998 (photo courtesy Reuters).

III. Experimental Measurements

Based on the preceding review of existing knowledge and available data, a program of multipoint measurements of atmospheric turbulence was undertaken using the techniques used in road vehicle testing. The measurements were taken a few meters above the ground, where it was envisaged that small MAVs used for reconnaissance, surveillance and disaster assessment would most likely operate, and in various open to moderately built-up terrains. The techniques of road vehicle testing were chosen because of the relative simplicity of setup that could take advantage of existing vehicles and road networks in suitable terrains, and the advantage of collecting data on a moving platform thus compressing the given “length“ of atmospheric data into a shorter time span. In addition, taking measurements in this manner better replicates how an MAV actually encounters turbulence in a particular terrain.

A. Required Spatial and Temporal Resolution

To achieve the objectives stated in Sec. II, it is necessary to define the temporal and spatial resolution most appropriate to MAV flight. The first of these, temporal resolution, can be achieved by appropriate instrumentation frequency response. MAV characteristic length can range from approximately 150 mm up to one meter in wingspan, with relevant chord lengths in a similar range. The turbulent scales of most relevance to the control of MAV flight are most likely within a range of $1/10$ to 10 times the wing chord/span, with overall MAV relative velocities ranging between approximately 0 to 10 m/s. Therefore the desired instrumentation frequency response that will achieve an appropriate temporal resolution is within 0.1–700 Hz. In contrast, spatial resolution simply needs to be much smaller than the MAV characteristic length of 150 to 1000 mm.

B. Important Parameters for MAV Flight

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 (obtained over 42 yr at a height of 10 m for a site in Australia, see [38]) reveals that the most probable wind speed is approximately 4 m/s and average wind speeds below 2 m/s occur for less than 10% of the time. Clearly the distribution varies with location height, terrain, etc. With a typical MAV flying speed of 10 m/s this limits the suitable ambient wind conditions to less than 10 m/s. Thus the area of interest for measurements of atmospheric turbulence with respect to MAVs is for wind speeds less than 10 m/s, with a bias toward the higher wind speeds within this range as these are the more difficult conditions to fly in.

The turbulence in the ABL provides for some unique challenges for MAVs. These can be broadly categorized into problems of stability and control. The former refers to the inherent stability of the aircraft and how it will respond to the aerodynamic inputs generated by the turbulence, whereas the latter refers to the methods employed to control the aircraft in its environment, maintain a heading or flight path, or actively maintain a position. Since one of the significant mission roles for an MAV is to provide real-time imaging, maintaining a stable platform for video cameras is particularly important. Therefore the effects of atmospheric turbulence on MAV stability need to be investigated, in order to achieve a stable viewing platform and provide the clearest possible pictures.

Aircraft motion can be described as translation and rotation about the 3 aircraft axes. This gives a total of 6 degrees of freedom. If we consider a camera pointing at a target some distance away, translation motions have a relatively small effect on the clarity of the image returned by the camera. Rotations about the axes have a much larger effect and are proportional to the square of the distance to the target. If the aircraft rotates a few degrees, then the distance the target moves in the camera field of view can be large. In the case of movements caused by gust inputs, which can occur at a high frequency, this type of motion can render a video image useless. It is therefore important to investigate this type of motion.

With regard to such rotational movements, for a camera that is required to look down on a target, then the rolling and pitching motions of the aircraft will have the greatest effect on image clarity. If the camera is pointing forward then the pitching and yawing motions have the greatest effect.

When flying through a turbulent environment, the aircraft response to gust inputs depends on its stability in a particular axis [3]. The less stable the aircraft is in a particular axis, then the greater its response to an input. Most conventional aircraft are greatly affected by pitch and roll movements, but not so affected by yaw. This is because such aircraft are directionally stable due to the relatively large distance between the vertical fin and the aircraft center of gravity, providing a “weather cocking” force like a weather vane and always pointing the aircraft into the direction of travel. Conventional aircraft are far less stable about the x- and y axes and thus more susceptible to pitch and roll inputs.

The aircraft “stick fixed” responses in pitch and roll (ignoring control inputs) are both attributed to the lift distribution over the main wing. If a gust front arrives at the leading edge, the wing will see an increase in velocity. If the gust front is uniform, and essentially two-dimensional, then the increase in lift will cause an increase in pitching moment and the aircraft will pitch up. As the gust leaves, the lift will reduce and the aircraft will pitch down. In this situation, it is the variation in longitudinal velocity with time, and particularly its frequency that is the important factor.

In the case of roll inputs, the gust front may be considered to be uneven along the span of the wing. As the gust front approaches the leading edge, the wing will see an increase in velocity, and therefore lift, at only certain portions of the wing relative to the rest of the wing. This local increase in lift creates an uneven lift distribution, thus causing a rolling motion. The variation in local pitch angle along the wingspan is a good measure of the possible roll inputs to an aircraft due to such a gust input.

In reality, most gusts caused by finer scale eddy motion in a turbulent flow will be more like the latter case, and much larger scale motion may approach the former two-dimensional case, although all are really three dimensional in nature. In the case of turbulence structures with very large scales, the effects may even be considered quasistatic, where the changes occur over such a large time scale that their effects are experienced slowly and are easily compensated for.

From this discussion it is apparent that the two more important parameters to investigate are those of velocity and pitch variation, in both time and lateral spatial separation. Pitch variations in time and space are involved in both pitch and roll inputs to an MAV platform and are therefore particularly significant. Two of the authors have significant experience in flying model aircraft and have noted that it is often the significant roll inputs that are the hardest to cope with when flying small aircraft in the atmospheric boundary layer. As these are caused by local variations in pitch angle along the aircraft wingspan, this parameter will be focused on in this paper, with future publications presenting further analysis including the effects of velocity variations.

C. Instrumentation and Configuration

Four turbulent flow instrumentation (TFI) multihole pressure probes, or Cobra probes (Fig. 3a), of 2.6 mm head dimension were used for testing using lateral separations of 150 and 50 mm, thus covering two "spans" of 450 and 150 mm, respectively. The probe heads were mounted 3.9 m from the ground, on a mast above a station wagon vehicle, and aligned nominally to the direction of motion (Fig. 3b).

The basic mast design consisted of a steel tube that was held by stays at multiple points in order to provide the stiffness required. Some problems were encountered early on in the testing program when the mast was only supported by a single set of stays and experienced resonance at ~7–10 Hz during vehicle motion. For calm wind conditions (1–2 m/s) the resonance vibration could be up to 50% of the flow velocity measured by the Cobra probes, as the motion of the mast caused an induced velocity at the probe head. The addition of a second set of stays significantly reduced the resonance problem, by approximately an order of magnitude, to a level that was considered acceptable and was not noticeable in the majority of all on-road measurements.

Multihole pressure 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 from 0 to greater than 1,000 Hz. Cobra probes do not replace hot-wire anemometers, but are a useful adjunct where the flow is greater than 2–3 m/s and 1% turbulence intensity, very fine spatial resolution is *not* required, but significant frequency response is required. In terms of measurements in atmospheric turbulence they are the most practical choice of instrumentation, as they will not suffer from broken sensing elements due to dust, debris, knocks, or sudden wind gusts, they measure fluctuating static pressure and all three fluctuating velocity components, have the required frequency response and are extremely stable with regard to changes in temperature.

Cobra probes are able to resolve all three components of velocity and static pressure, as long as the flow vector falls within a cone of ±45 deg around the probe x axis. This enables resolution of the constantly fluctuating velocity vector in turbulent flow while the probe is approximately aligned with the free-stream flow direction and the turbulence intensities are not excessively large (below 30% turbulence intensity in the y and z directions is preferred). Data that fall outside the ±45 deg acceptance cone are indicated by the software. Accuracy of measurements is somewhat dependent on turbulence levels but is generally within ±0.5 m/s and ±1 deg pitch and yaw up to about 30% turbulence intensity. The Cobra probe remains relatively accurate in flows with greater than 30% turbulence intensity. The particular type of probe used for these measurements had 2.5 kPa (0.3 psi) pressure transducers, and was dynamically calibrated by the manufacturer to allow accurate flow measurements up to ~50 m/s. Measurement spatial resolution was determined by the size of the probe head (2.6 mm) thus allowing accurate resolution of flow structures down to ~25 mm. The Cobra probe capabilities thus achieve the desired frequency response and have a spatial resolution much less than an MAV characteristic length. Details of the system and examples of use can be found in [39] and verification and further details, including dynamic capabilities, can be found in [40,41]. (Descriptions of the probe operation methodology and calibration techniques, along with a confirmation of their accuracy, are given in [40,41]. The manufacturer applies the described calibration methods to all probes before delivery and recalibration is not required unless a probe is significantly bent or damaged.)

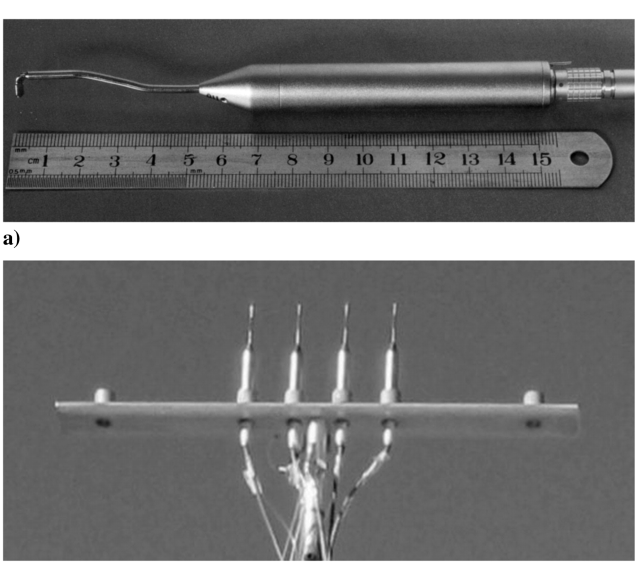

Fig. 3 Test instrumentation: a) multihole pressure probe; b) four probes mounted on a mast.

D. Test Procedure

The multihole probes were supplied by the manufacturer already calibrated for velocity and frequency response and required only occasional static calibration to check the transducer Volts-to-pressure ratio. To check the alignment in pitch and roll of the vehicle-mounted probes, referenced to the horizontal plane and direction of travel, calibration runs were performed at various speeds from 20 to 60 km/h under relatively calm conditions. The measured pitch and yaw offsets were then removed from all subsequently measured data. The proximity effect of the car body on velocity was also accounted for as the vehicle speed was measured using a GPS (global positioning system) unit. 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, even at 100 km/h, and it was found to be negligible for the test speeds used here.

Measurements for the entire test program were performed on straight, approximately level sections of road, approximately into the prevailing ambient wind, at a constant vehicle speed appropriate to the road being tested on (usually 20 or 50 km/h), with little or no traffic. Measurements were also taken with the vehicle stationary, pointing into the prevailing ambient wind, in order to document the atmospheric winds. A variety of terrain types were used for the measurements, ranging from roughness categories 4 to 7 as classed by [42], or category 3 to 4 in [43]. This encompassed open farmland with low crops or plant cover and occasional obstacles separated by ≥ 20 obstacle heights, to built-up suburban and metropolitan areas with full, similar-height obstacle cover and obstacle separation of the same order as obstacle height. A large volume of data was recorded and only selected portions are presented here.

At a lateral spacing of 50 mm, the four probes were simultaneously sampled at 5000 Hz to avoid aliasing and the data were filtered and down sampled to an output data rate of 1250 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 up to 9 m/s there is little turbulent energy above 250 Hz depending on vehicle speed, and such a sampling frequency covered the majority of the range relevant to MAV flight as detailed in Sec. III.A.

For the moving vehicle runs with a lateral probe spacing of 50 mm (total span 150 mm) a sample length of 30–60 s was used, depending on the length of road segment available and the available traffic conditions. For documenting the atmospheric wind (i.e., vehicle stationary) 600 s samples were used and these data were captured while the vehicle was parked close to the start or end of a moving run, at locations that were selected to be away from local effects (buildings, trees etc.).

Early testing conducted with a lateral probe separation of 150 mm (total span 450 mm) used an output data rate of 375 Hz, sample lengths of 10 s for moving vehicle runs and 100 s for stationary measurements. (This is a very short sample time for calculating wind characteristics, but was a limitation of the instrumentation used at the time. This does not influence the results presented here, except the calculation of length scales as discussed later on. Wind engineers typically use sample durations ranging from several minutes to 1 h for such calculations, with the data thus falling in the "spectral gap" that separates the microfluctuations from the macro.) Data from these tests have also been included in the results presented here as they illustrate turbulence characteristics over a total span of 450 mm, as compared with 150 mm for the closer probe spacing. Selected results from this early testing were previously reported by [44].

E. Data Processing and Analysis

Once the data were acquired and offsets removed, they were corrected for the yaw angle of the relative flow to the vehicle direction of travel, or probe orientation for stationary measurements. Because of this yaw angle, packets of turbulence effectively arrived at the probes at different times, and correcting for this thus involved time shifting the data depending on the probe relative position and the relative flow speed and yaw angle. As the majority of measurements were taken in conditions into the wind, with relatively small yaw angles, the resulting corrections were typically small, of the order of 1–6 samples or 5 ms between the fourth and first probes and less for the probes in between.

After the data were appropriately time shifted, the overall mean yaw angle was removed. These corrections effectively simulated a head-on wind condition at the instrumentation mounting, and standardized the data so that the main variables between different test runs were only the ambient wind conditions and terrain type. All data were also analyzed both with the vehicle speed included, and with the vehicle speed mathematically removed from the data. The latter results were compared with data measured with the vehicle stationary, to check for validity, and were used to provide information on the turbulence characteristics MAVs would experience at very low (or zero) effective ground speed.

With the preprocessing complete, various statistical properties of the data (both with and without the vehicle speed included) were calculated for each measurement. These included average relative and component velocities, pitch (or equivalently: angle of attack) and yaw angles (α, Ψ), and standard deviations of the same parameters. Turbulence intensities for the three orthogonal directions were also calculated, as illustrated by Eq. (1) for the longitudinal turbulence intensity of the ambient wind.

$$I_u = \frac{\sqrt{\overline{(u')^2}}}{\overline{V_w}} = \frac{\sigma_u}{\overline{V_w}}, \quad \text{where } \overline{V_w} = \overline{\sqrt{u^2 + v^2 + w^2}} \tag{1}$$

Once these quantities were calculated, power spectral densities (energy spectra) of the velocity and flow angle fluctuations were calculated, as well as the pitch variation fluctuation (standard deviation of the pitch variation between the variously spaced probes —see section below for further discussion). The latter gave fluctuation magnitudes in pitch variation for spacings of 50, 100, and 150 mm for the 50 mm spaced probe array, and for 150, 300, and 450 mm for the 150 mm spaced probe array. Power spectra were calculated using no data window, and averaging the 2048-point spectra using 50% overlap.

Pitch angle coherence between the variously spaced probes was also calculated, thus giving a measure of the amount of pitch angle correlation versus frequency between the different measurement positions. Finally, the 600 s stationary measurements were used to estimate longitudinal turbulence length scales for the given atmospheric conditions and local terrain. Autocorrelation of a velocity measurement at a single point in space, using Taylor's frozen turbulence approximation, was performed in order to estimate the longitudinal length scale of the flow. Because of the relatively short time samples and the fact that Taylor's approximation did not always hold, the calculated length scales were only rough estimates.

1. Pitch Variation Fluctuation

As the effective roll inputs to an MAV wing were of importance, and this depended on the difference in pitch angle (angle of attack) experienced at different points along the wingspan, pitch variation was defined as the difference in pitch angle between two laterally spaced points in space, Eq. (2). Lateral spacing refers to the horizontal separation perpendicular to the vehicle orientation or direction of travel.

$$\Delta\alpha_{ij} = \alpha_j - \alpha_i \tag{2}$$

Therefore a measure of the magnitude of fluctuation in the pitch variation between two such points is given by the standard deviation of the pitch variation, $\sigma_{\Delta\alpha}$, or pitch variation fluctuation. This quantity has units of degrees (deg) and has a direct impact on the difference in lift generated at two points on a wingspan, and therefore on the amount of roll input to an MAV wing.

Pitch variation fluctuation is an overall measure of the roll input for a given lateral spacing, and does not take account of the frequency information contained within the turbulent structures (i.e., turbulent length scales). This is analogous to the way that turbulence intensity is an overall measure of velocity fluctuations but contains no information about the magnitude of those velocity fluctuations with frequency. However, the lateral spacing in itself ensures that the pitch variation fluctuation only contains information from the smaller length scales (in effect acting as a high pass filter), as length scales of the order of or larger than the measurement point spacing should have a similar pitch angle at the two points and therefore not contribute significantly to observed variations in pitch angle along the wing span. In this respect, some frequency information is contained within the pitch variation fluctuation parameter, as well as it being a measure of the overall roll inputs to an MAV wing in atmospheric turbulence.

IV. Results and Discussion

Testing was conducted over the course of a month with atmospheric wind speeds varying from 1.5 to 9.5 m/s during measurements in terrains of roughness [42] 4 to 7. Both stationary and moving measurements were taken, with the latter typically of 45 to 90 s duration at 20 or 50 km/h vehicle speed, whereas the former were of 600 s duration with the vehicle stationary but pointing into the prevailing wind. Measurements were taken 3.9 m above the ground, with the four multihole pressure probes either at 50 or 150 mm spacing.

The variation in overall mean relative velocity between the four probes for any given measurement run (over the entire testing program) was ±0.2 m/s at 95% confidence (assuming a Gaussian distribution in variation between the probes). Turbulence intensity magnitude measured directly by the probes during moving measurements (i.e., measurements including vehicle speed) were less than 20%, and generally less than 10%, and therefore well within the probes capabilities. For stationary measurements, turbulence intensity generally ranged from 15 to 35%, still within the Cobra probes core region of accuracy. However, intermittent data dropouts affected some of these latter measurements, due to the wind fluctuations varying outside the ±45 deg acceptance cone of the probes. The variation between the longitudinal turbulence intensity measured by the four probes for any given moving measurement was within ±0.002 at 95% confidence. While for stationary measurements it was within ±0.003 at 95% confidence for measurements without dropouts, and ±0.01 at 95% confidence for those measurements with data dropouts. All of this was considered reasonable precision for the type of measurements being taken, and the repeatability between the measurements of the four probes and between consecutive measurement runs gave confidence in the resulting data.

A. Moving Through Turbulence

When an extra mean velocity is superimposed on the atmospheric wind, in this case by moving a vehicle at a constant speed through the

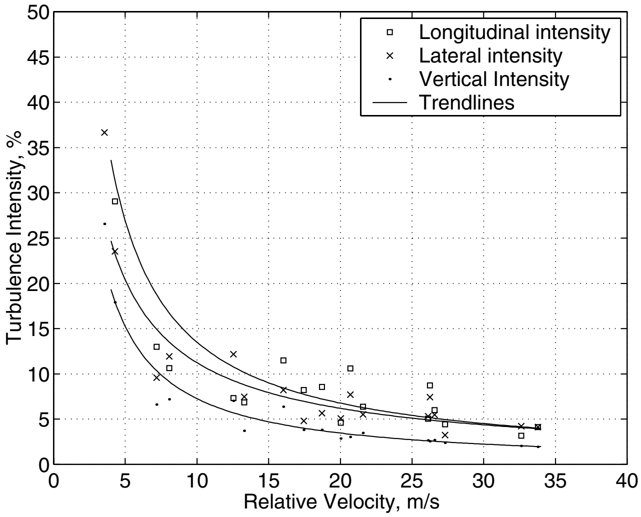

Fig. 4 Reducing turbulence intensity with increasing object speed (uncertainty in J is ±0.5% at 95% confidence).

ABL while taking measurements, the magnitude of perceived flow angle fluctuations and turbulence fluctuations reduce, as shown by comparing Eq. (3) to Eq. (1).

$$J_u = \frac{\sqrt{\overline{(u')^2}}}{\overline{V_r}}, \quad \text{where } \overline{V_r} = \overline{\sqrt{(u + V_{\text{Veh}})^2 + v^2 + w^2}} \tag{3}$$

The addition of a mean speed component does not change the magnitude of turbulence fluctuations in the numerator, but it does increase the mean relative velocity in the denominator, this reducing the perceived turbulence levels. This is illustrated graphically in Fig. 4 using data taken consecutively in a single test session at vehicle speeds of 0, 40, 60, 80, and 100 km/h with an overall average ambient wind speed of 4.6 ± 0.3 m/s. Despite the slight variations in ambient wind conditions for each subsequent measurement, the trend lines clearly show the decrease in turbulence levels as the overall relative velocity is increased by the increasing vehicle speed. This has been previously illustrated in [32,33], where a predictive method for calculating the fluctuating vectors and turbulence intensities experienced by a moving object from atmospheric wind data were provided.

As both pitch and yaw flow angles also have the mean u-component velocity in the denominator, the addition of a mean vehicle speed in the x direction also increases the denominator although leaving the numerator unchanged, thus decreasing the perceived flow angles. This is why it is advantageous to take turbulence measurements on a moving platform, as both the flow angles and turbulence levels are limited to a more manageable range that is better suited to the instrumentation. Any known mean speed component can then be removed at a later stage during data processing. This is also why an MAV flying into atmospheric turbulence at a given speed will experience lower effective pitch and roll inputs than if it was maintaining an effectively stationary position, that is, hovering, in the same ambient wind conditions, and why flying downwind (depending on the indicated air speed) can be more deleterious with regard to pitch and roll inputs).

B. Pitch Variation

Example results from measurements taken with the four probes in typical atmospheric wind conditions and fairly open terrain are shown in Fig. 5. The data were from a stationary measurement in open farmland, roughness category 3 [43], wind speed 7.8 m/s. (Note that in Fig. 5 the uncertainty in pitch angle is ±1 deg at 95% confidence.) Immediately apparent in Fig. 5a is the large variation in pitch angles (±10 deg) with time, but the plot lines for the four probes appear to have similar instantaneous pitch angles that are reasonably well correlated. Closer examination in Fig. 5b (showing a

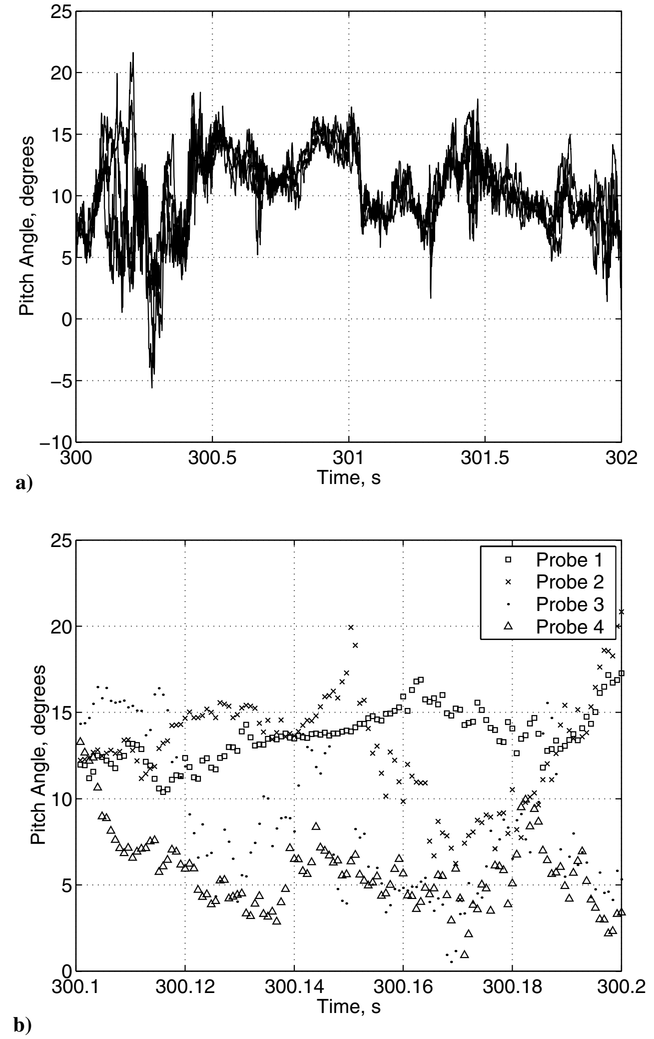

Fig. 5 Pitch angle versus time: a) 2 s sample; b) 0.2 s sample.

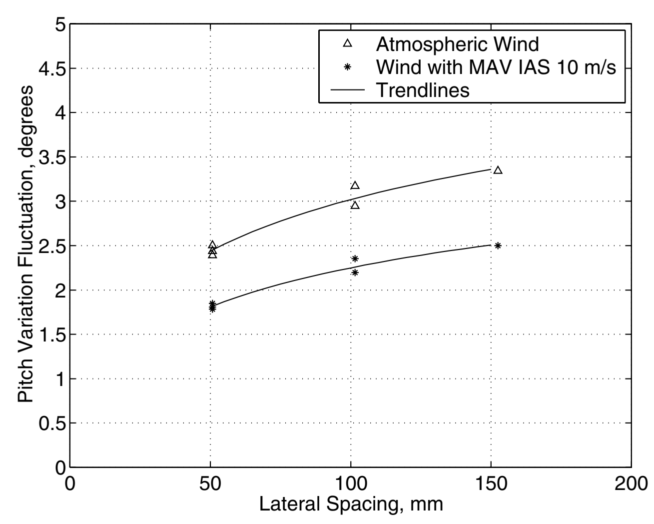

Fig. 6 Pitch variation fluctuation versus measurement spacing.

zoomed in portion of the same data) reveals that there are considerable differences in pitch angle, at times ∼15 deg between probes 2 and 3, despite a lateral separation of only 50 mm. Similar results were also found for the instantaneous yaw angles and flow velocities in a variety of terrains and wind conditions.

The magnitude of instantaneous pitch angle variations with lateral separation can be examined by plotting the pitch variation fluctuation

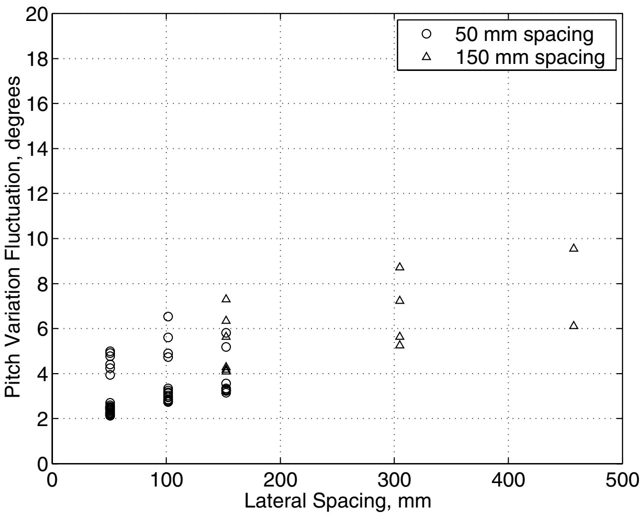

Fig. 7 Pitch variation fluctuation for all stationary measurements.

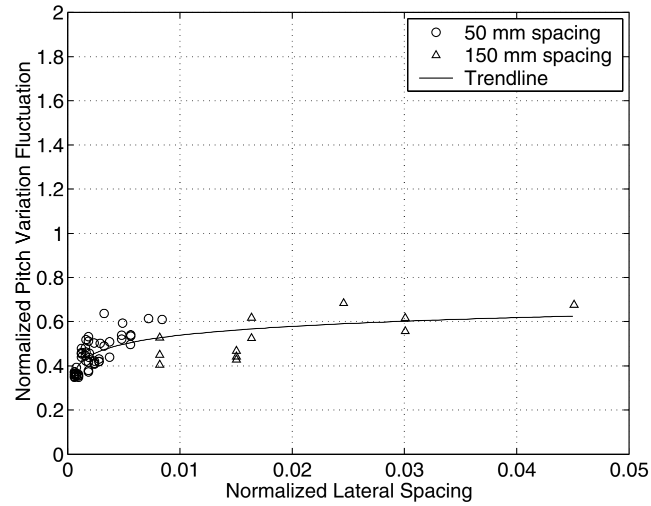

Fig. 8 Normalized pitch variation fluctuation for all stationary measurements.

$\sigma_{\Delta\alpha}$ versus measurement separation for the same data (Fig. 6). This figure shows that the magnitude of pitch variation fluctuation decreases with decreasing lateral separation. This was the case for all data taken during the on-road measurements. Note that there are 6 data points plotted for a given measurement using four probes because all combinations of probe spacing are represented: three 50 mm spacings between probes 1 to 2, 2 to 3, and 3 to 4; two 100 mm spacings between probes 1 to 3, and 2 to 4; and finally one 150 mm spacing between probes 1 to 4. Also shown plotted against the experimental data are their trend lines, which for all measurements in all wind conditions and terrains was logarithmic in nature, with a regression coefficient of greater than 0.95 and often greater than 0.99.

Figure 6 shows the pitch variation fluctuation for two particular cases: that of the atmospheric wind only; and that of the atmospheric wind with a mean u component added to it in order to simulate an MAV flying into this wind at an indicated air speed (IAS) of 10 m/s. (An IAS of 10 m/s was used as a standard reference point during the research project. Although somewhat arbitrarily chosen, this speed is considered a fairly typical flying speed for the size of MAV considered here.) As the mean atmospheric wind speed for this particular data was 7.8 m/s, this involved adding a mean u component of 2.2 m/s to the raw data. This figure graphically illustrates how moving through atmospheric turbulence reduces the perceived pitch angles and pitch variation fluctuation, and thus reduces the effective roll inputs to the moving object (again emphasizing that holding a stationary position against the wind is more challenging than moving into the wind). The increased turbulence levels and pitch variation fluctuations at very low or zero ground speed thus provide significant challenges for attitude control in MAVs and may require radical new approaches to small aircraft design, such as flapping propulsion or flexible wings.

If selected data from the test program are plotted on the same plot without any normalization, Fig. 7 results (the reason for only plotting a selection of the data will become apparent after the following discussion). As can be seen in Fig. 7, the data are scattered with no obvious collapse of the data onto a single trend.

An attempt to normalize the data was performed by considering both the independent variable (measurement spacing) and the dependant variable (pitch variation fluctuation). For the latter, as it is the standard deviation of the difference in pitch angle between two points, the standard deviation of the pitch angles at the individual points would seem appropriate measures for normalization, Eq. (4a). For normalization of the independent variable, the spacing between measurement points has dimensions of length, and it is expected that the difference in pitch angle between two laterally spaced points would depend on the length scale of the turbulent flow structures that are convecting past those points. So it seems reasonable that the characteristic length scale of the turbulent flow would be appropriate to normalize the measurement point spacing, Eq. (4b).

$$\frac{\sigma_{\Delta\alpha}}{\sqrt{\sigma_{\alpha_i}\sigma_{\alpha_j}}} \tag{4a}$$

$$d/L_x \tag{4b}$$

If the same data from Fig. 7 are taken and normalized according to Eq. (4), Fig. 8 shows the results, along with a trend line that was again logarithmic in nature. Note that in order to get reasonable estimates of the length scale L_x, it was necessary to use only data that had particularly long time samples, for example, 5 min or greater. This was the reason for using only a selection of the data, as many samples were relatively short (~60 s). The data used in Figs. 7 and 8 are therefore limited to terrains where long measurements were taken; typically more open farmland, rather than built-up areas, as there was more chance of getting samples uninterrupted by traffic and in positions not in the immediate wake of any particular object. Data taken with the 150 mm probe spacing were an exception in that the time samples were of 100 s duration, as these data were from early investigatory measurements taken prior to the current instrumentation configuration.

There is a fair amount of scatter in the results shown in Fig. 8, most likely due to the uncertainties in the length scale values (although uncertainty in the length scale due to the equipment used was certainly within 5–10% at 95% confidence, consecutive measurements exhibited a standard deviation of 10–20% due to insufficient sample length and the ambient wind characteristics changing with time) which were very hard to consistently determine even with 5–10 min samples. Normalizing the measurement spacing using L_y produces a similar collapse of the data, with a logarithmic trend with a slightly lower regression coefficient. Without better length scales estimates it is not possible to evaluate the relative merits of normalization using L_x or L_y, although as the measurements are laterally spaced, L_y may be a more rigorous choice of normalization parameter. However, the results show that some collapse of the data is achieved by using the normalization given in Eq. (4). Further work is planned in this area and in examining the underlying relationships that explain this behavior. Regardless of the underlying relationships, the fact that the nondimensional data appear to collapse indicates that it should be possible to describe the behavior of pitch variation fluctuation with a relatively simple function, thus allowing the likely turbulence characteristics in a given terrain to be estimated based upon a known length scale and turbulence level. This would be of great benefit in MAV design, computational modeling, and wind tunnel testing.

C. Coherence

The pitch variation fluctuation only indicates the overall magnitude of fluctuations in pitch variation. It does not indicate how

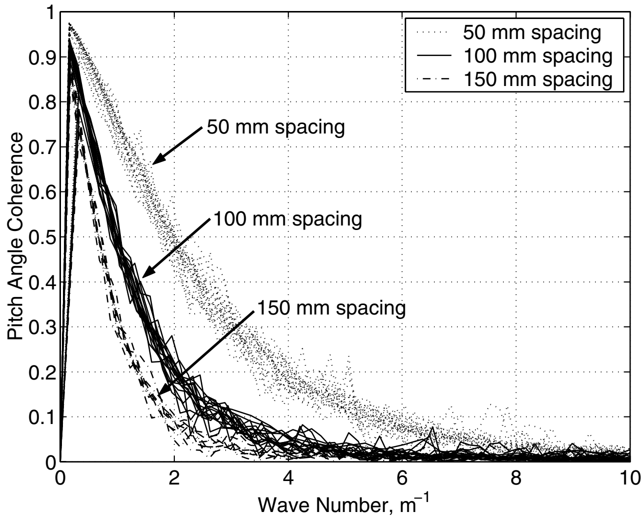

Fig. 9 Pitch angle coherence for all stationary measurements.

the pitch angle experienced along an MAV wingspan might change with the turbulence scale or eddy size. To do this, it is necessary to examine the pitch angle coherence C_{ij} (essentially a normalized cross-spectral density of pitch angle), between the measurement points, as shown in Fig. 9. (Note that in Fig. 9 the uncertainty in the spectral processing is $\pm 6\%$ at 95% confidence due to the long time sample and averaging technique used, while uncertainty in pitch angle is ± 1 deg at 95% confidence.) Although Fig. 9 shows only the results from the stationary measurements for reasons of clarity, results from the moving measurements in all terrains showed the same collapse against wave number k with the coherence falling into the same bands as shown in Fig. 9 based on the lateral separation between measurement points. The data show that at larger lateral separations, the pitch angle coherence between different points in space falls off more quickly with increasing frequency, or reducing turbulence scale. This means that with larger packets of turbulence (relative to the spatial distance between the measurement points) a similar pitch angle is experienced at both points in space, whereas with the smaller turbulence scales the pitch angle at the same two points has much less or no correlation. This is an intuitive result, but the data in Fig. 9 and the collapse against wave number can be viewed as a useful tool for predicting the amount of correlation (and therefore the likely pitch variation) for a given turbulence scale and MAV wingspan. As coherence is a normalized quantity, it does not indicate the magnitude of the likely variation but this may be inferred from the likely turbulence levels for a given terrain and wind speed.

The results from this research, of which a small portion is presented here, thus represent both a database of turbulence characteristics in different terrains and wind conditions, as well as provide valuable predictive tools to assist both computational modeling and dynamic design of MAVs. With the knowledge of how turbulence characteristics are likely to vary along a typical MAV planform, it will be possible to use this data as input to computational models, or to replicate selected, relevant portions of atmospheric conditions within a wind tunnel, in order to test prototype MAVs. The latter task is one that our group is already working on and the results of this phase will be reported in future publications.

V. Conclusion

The data presented appear to be one of the first attempts at recording some of the many possible flow environments of MAVs, albeit at an altitude of ~4 m. There are, of course, an infinity of possible atmospheric wind speeds and turbulence characteristics (and flight direction relative to the wind direction) that will vary with altitude, terrain, and climatic conditions, but these results represent a start at documenting this environment and examining the turbulence characteristics most relevant to the flight of small aircraft with wing spans in the range of 450 mm to 1 m.

Unlike the majority of wind engineering data sets, the measurements taken here were for elevations that were within the lower part of the ABL roughness zone, close to the ground. It should be noted that this is the environment in which MAVs are envisaged to collect data. The current measurements were in fairly open to moderately built-up terrains, but because the proposed environment of MAVs is also through highly irregular terrain such as city canyons where very disturbed flow environments exist, further work is considered necessary in this area. The data taken here were also exclusively in fairly developed flows, with the measurement runs several kilometers within the terrain of interest and not in the immediate wake of large obstacles. MAVs will, however, have to fly in and around large obstacles as a matter of course and future measurements should examine the transient flow field experienced as an MAV traverses obstacle wakes in a given terrain and wind condition.

The current results have concentrated on the spatial variation in pitch angle along an MAV wingspan, that is, in a lateral direction, as this is considered a significant influence on the effective roll inputs of MAVs. The investigation in different terrains and wind conditions has shown the large variations in pitch angle possible at even relatively close distances, and that there appears to be a relationship between the overall amount of pitch variation, the lateral spacing and the turbulence characteristics. The amount of correlation in pitch angle with lateral spacing and turbulence scale has also been shown to have a consistent pattern, and both of these results will require further investigation to evaluate and better define them. However, it is felt that they will be useful tools for the future design, development, and testing of MAVs.

Further processing of the data sets gathered here is planned, including further analysis of the parameters affecting the pitch inputs to an MAV (e.g., velocity variation), and investigation of the effects of the turbulence on the motion of MAVs (from measured aerodynamic derivatives). It is also planned to evaluate whether or not portions of the atmospheric turbulence most relevant to MAV flight can be replicated in a wind tunnel, thus simplifying the testing of prototype MAVs. This latter task is already under way and the results from it will be reported in future publications.

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 450 to 150 mm appears to make relatively little difference to the variation, indicating that the roll rates induced by turbulence would increase as span reduces.

The potential roll inputs are of such significance it is speculated that to hold a relatively stable viewing platform, flapping wings (or to a lesser extent rotor flight) may be required. These offer interactive control advantages over conventional fixed wing flight. It has been noted that with decreasing scale the efficiency disadvantages of rotor flight, compared to fixed wing flight, reduce. Clearly there is some way to go before we can emulate small-scale natural flight and how it has adapted to the turbulent wind environment, but the results presented here and further planned analysis will provide the information required to focus MAV design strategies.

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