Turbulence Characteristics of the Atmospheric Boundary Layer and Possibilities of Replication for Aircraft

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Abstract

Existing data of atmospheric turbulence close to the ground are reviewed for the purpose of understanding the relative turbulence characteristics experienced by aircraft taking off and landing. Measurements from laterally separated probes demonstrate that the high frequency part of the turbulence spectra closely follow the well-known 5/3rds Kolmogorov spectral decay when locations well away from local effects (e.g. building wakes) are considered. The concept of testing aircraft in scaled replications of the atmospheric boundary layers (in a similar way to wind engineering) is considered.

Nomenclature

f frequency (Hz)

I_i turbulence intensity of the ambient wind defined as σ_i, V_r, where i can be u, v or w,

J_i turbulence intensity perceived by a moving object, where i can be u, v or w

k wave number (= f/V_r)

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)

S_{uu} power spectral density in the along wind direction, calculated as above

t time (s)

T sample time (s)

V_r overall relative air velocity magnitude (= $|\mathbf{V}_r| = \sqrt{u^2 + v^2 + w^2}$) this can be either the mean atmospheric wind speed (earth reference frame), or the mean indicated airspeed (IAS) experienced by the moving aircraft

u, v, w velocity components in the x, y, and z directions respectively

z elevation (m)

z_0 surface roughness parameter (m)

α pitch angle [= $\tan^{-1}(w/u)$]

σ_i standard deviations of velocity fluctuations, where i can be u, v or w

– denotes a time-averaged or mean component

‘denotes a fluctuating component (mean component removed from the variable

1 Introduction

Commercial and military aircraft spend most of their flight time in cruise configuration well above the Earth’s atmospheric boundary layer (ABL) and generally fly at high speed through air that has negligible levels of turbulence. Research and development for military and commercial aircraft has thus been in a smooth flow domain – either experimental or computational. However during takeoff and landing relatively high levels of turbulence are often experienced since speeds will be appreciably lower than cruise speed and when atmospheric wind is present aircraft will experience the turbulence and shear that is inherent in the ABL.

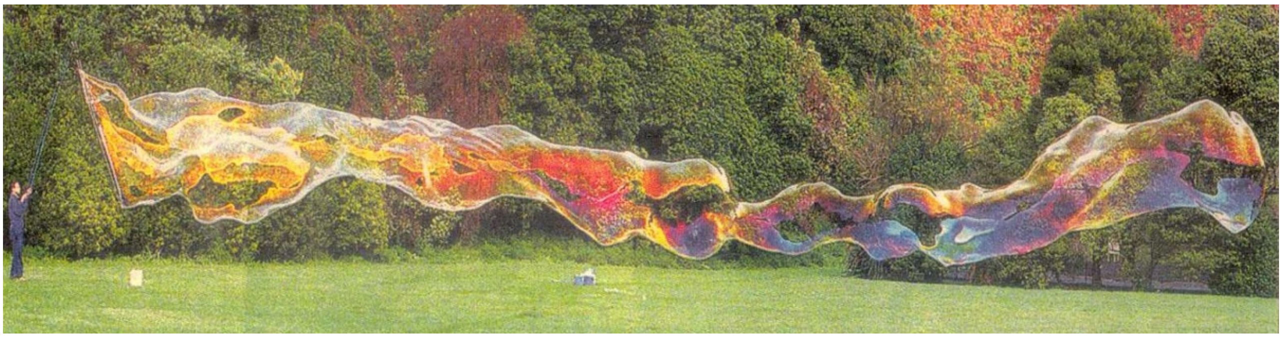
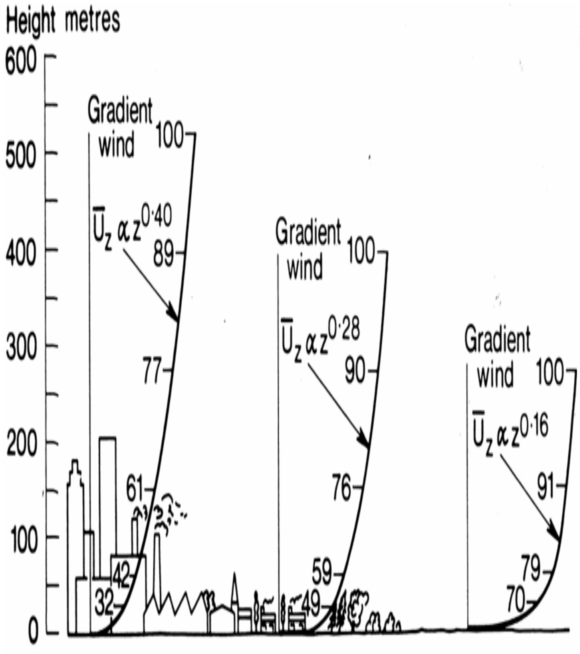


Figure 1 The longest bubble in the world (courtesy A. McKay, copyright G. Norman).

A depiction of atmospheric turbulence close to the ground is given in Figure 1 (note the person standing in the left hand side for an indication of scale). Distortion of the soap film shows the small-to-medium scale structures in the first few metres of the ABL. The influence of eddies of various scale is evident, ranging from less than half a metre to approximately 15 metres (the total length of the bubble is 32 metres). Vorticity about a horizontal axis is apparent one-third of the way along the bubble and also towards the end.

The ABL extends from the Earth’s surface up to an altitude where the wind is no longer influenced by the roughness of the ground and the mean wind speeds increase with height up to the gradient height, usually defined as the height above ground where surface friction has a negligible effect on wind speed. Above this height the air is generally smooth, with the exception of bursts of “clean air turbulence” which is not considered here. The variation of mean velocity (denoted U_z in Figure 2) and turbulence intensity (denoted $(\sigma_u)_z/U_z$ in Figure 3) with height z has been studied for many years in the field of wind engineering [1]. Turbulence characteristics are influenced by the thermal stability of the atmosphere (adiabatic, or various degrees of stability) [2,3], but under strong winds mechanical mixing tends to dominate the turbulence generation mechanism and thermal stability plays a smaller role. Since strong winds will be the most influential on large aircraft, the effects of varying thermal stability will not be considered further here.

On, or very close to the ground, aircraft will be travelling through the “roughness zone” where the wakes of the local surface obstructions are significant and increase the turbulent energy levels while reducing the mean velocities. This is also true for ground-based craft (cars, trains etc.), and there is an increasing body of knowledge focused in this area arising from safety and stability concerns and interest in transient aero acoustics [e.g. 4- 9]. The advent of micro air vehicles (MAVs), where man attempts to duplicate nature’s flyers, has also furthered the need to understand turbulence close to the ground, since MAVs are light, fly at relatively slow speeds and are limited to typically less than 100m altitude [e.g.10-14]. Work in this area includes dedicated measurements of atmospheric turbulence from both stationary and moving perspectives, as described later.



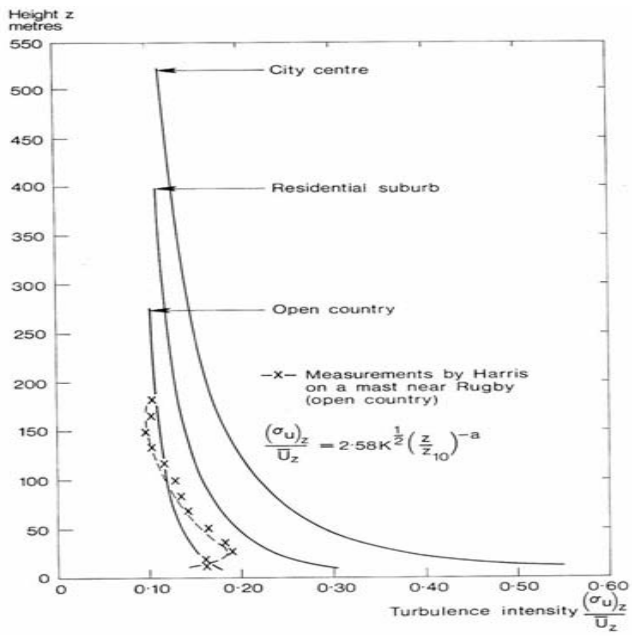


Figure 2 Mean wind velocity profiles and; Figure 3 Turbulence Intensity profiles for a range of ground roughness, both adapted from[1]

A large volume of work exists on understanding the turbulence inherent in atmospheric winds and its effects on the response of structures [e.g. 15]. Military specifications for the modeling of turbulence are given in MIL-F-8785C and MIL-HDBK-1797, and turbulence inputs to aircraft dynamics and control can be found in several texts [e.g. 16]. The military specifications are used to generate a simplified statistical model of wind turbulence to be used as an input to a dynamic model of an aircraft. For simplicity the models are often divided into two altitude ranges, low altitudes ("less than or equal to 1000 ft") and the medium/high range. Inputs to these models are very simplified descriptions of length scales and at the surface the descriptions assume that the scales tend to zero. This is a great simplification and loses physical significance and is considered later.

There has been negligible work on replicating turbulence in wind tunnels or CFD for aircraft whereas 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. Recent research extends the replication of atmospheric turbulence to studies on model and full-scale road vehicles (see for example [17]).

Knowledge of how the flow environment is likely to vary in time and space is useful for computational models and physical replications of the flow. Whilst there have been several single point models of turbulence proposed for simulating the dynamic inputs to aircraft [18, 19], Etkin [20] saw the requirement to make measurements from laterally separated probes, in order to understand the temporal and spatial variation of the flowfield relevant to aircraft taking off and landing in windy conditions. He suggested a series of measurements up to the maximum frequencies of interest, made at points representing the path of the aircraft through a variety of atmospheric conditions to enable a further understanding of the disturbances.

1.1 Objectives

It is the aim of this paper to review meteorology and wind engineering data for heights relevant to aircraft taking off and landing and to consider the possibilities of replication of such turbulence as experienced by aircraft moving at various speeds through the ABL. Additionally some limited atmospheric data from measurements performed for micro air vehicles using laterally separated probes are provided, as suggested by Etkin [20].

2 Existing meteorological and wind engineering knowledge

The ABL has been documented by many researchers and information has been obtained by meteorologists and 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. [e.g. 21-28].

Mean wind speeds with height above the ground, climatic conditions, time of day, month of the year, location, elevation, etc. Data can be found from meteorological agencies for specific locations and times. An example is provided for illustrative purposes, see Figure 4a. These data are for a coastal site and it can be seen that the most likely wind speed is of the order of 6 m/s and the likelihood of experiencing calm is about 7%. Generally coastal sites will have higher mean speeds than centrally located sites. In Fig 4b the variation of mean monthly wind speed is shown for a city and the average wind speed is about 11 Km/h (~3 m/s). There is a large and growing database of such wind statistics for developed countries.

From the perspective of a wind engineer it is essential to consider the likely maximum levels of mean and peak atmospheric winds and it is common to fit probability distributions to data sets in order to predict maximum loading levels of buildings, masts etc. However aircraft have given criteria regarding the maximum wind speeds at which they are permitted to take off and at higher speeds they will be grounded. This varies with aircraft size, mass, and the angle between the mean wind direction and the runway. It is common to place the most restrictive maximum permissible takeoff wind speed for a crosswind condition. However the highest range of streamwise relative turbulence intensities will be experienced for headwind or tailwind directions; see later.

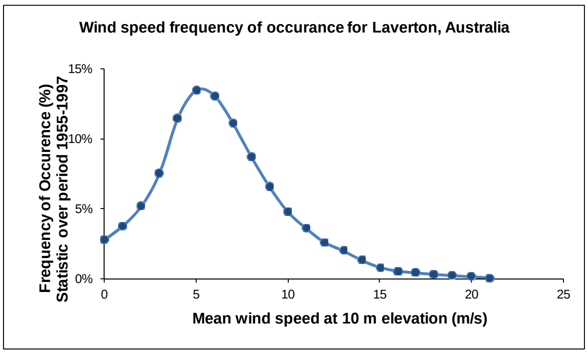


Figure 4a Typical probability of occurrence

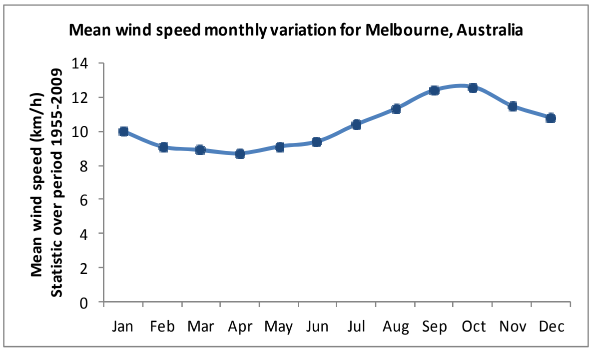


Figure 4b Typical monthly variation from www.bom.gov.au)

Turbulence intensities for the three orthogonal velocities give a measure of relative gustiness in the atmosphere, and for the longitudinal turbulence intensity measured from a stationary reference frame;

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

For the lateral and vertical directions the fluctuating longitudinal velocity *u*' is replaced with *v*' *or w*'. The variations of the three orthogonal intensities in the vertical direction, up to about 20m, have been measured in detail for "suburban terrain" by Flay [29], see Figure 5. From such measurements it can be seen that the along-wind component (u) is greater than the cross-wind and vertical components (v, w) and with increasing closeness to the ground the turbulence intensity increases and changes characteristics. 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 metres and the integral length scales can be seen to be of the order of several metres even at 3m from the ground surface.

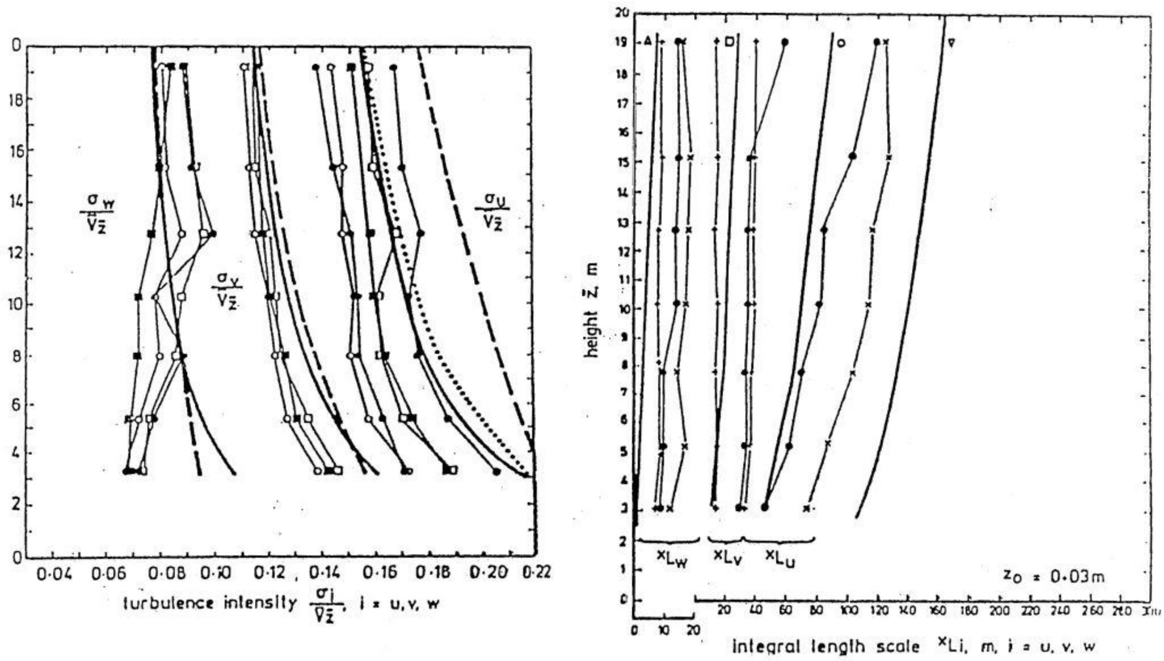


Figure 5 Turbulence intensities and scales for "suburban terrain" as a function of elevation very close to the ground, from Flay[29]

A review and compilation of many sources on the ABL (including the data of Flay) can be found in the Engineering Sciences Data Unit (ESDU) data sheets. ESDU 85020 [26] summarises single point data to 1985. ESDU 86010 [27] details the variations in atmospheric turbulence in space and time for strong winds. Some multi-point data sets exist; however most multi-point measurements are separated in the vertical direction reflecting the main interests of the wind engineers. For aircraft measurements are most useful when they are separated laterally and the separation distance is of the order of the aircraft span. Such data sets appear rare.

The local terrain roughness is usually described by a length scale z_0. Typical values for very smooth terrain (flat deserts or plains) are 0.001 to 0.003, small towns and their outskirts 0.1 to 0.3 and large city centres 0.7 – 1.0 [EDSU 85020]. These values can be used to predict the turbulence intensities at different elevations (z) from Figure 6.

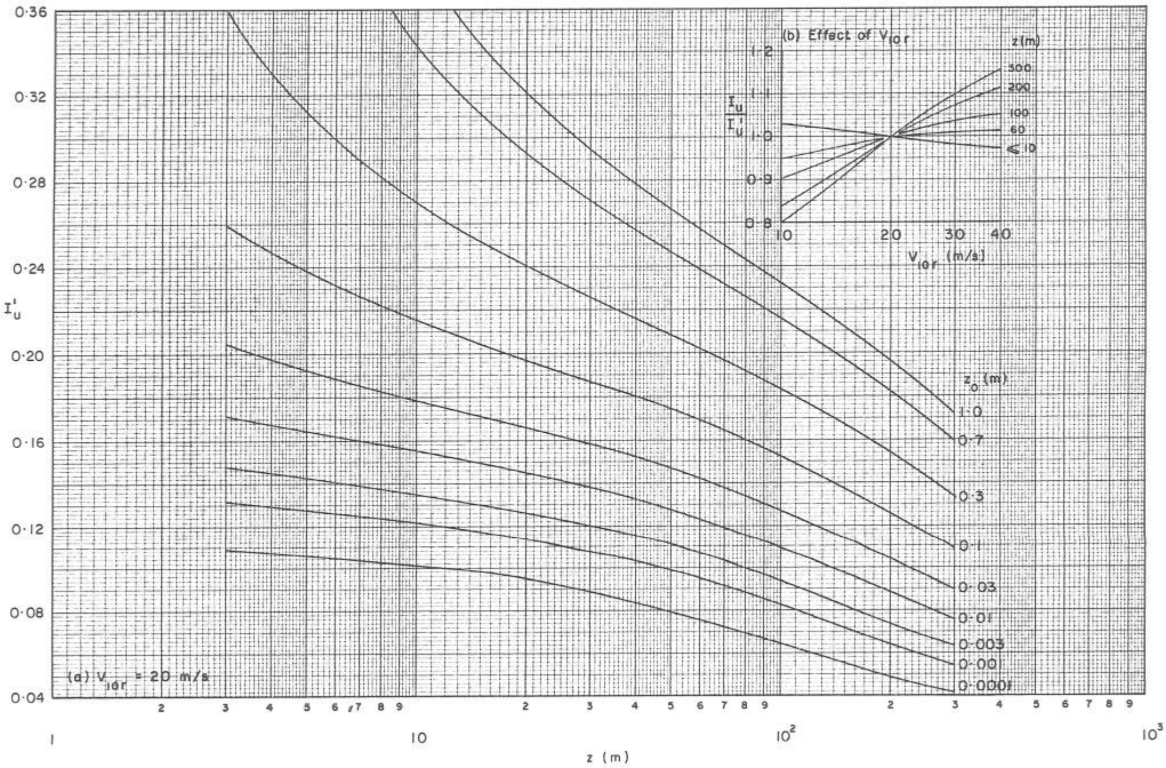


Figure 6 Longitudinal turbulence intensities for equilibrium conditions
from ESDU 85020 [26]

The spectra of the three orthogonal velocity components provide descriptions of the energy as a function of frequency. There is a wealth of data from wind engineering and meteorological measurements on this topic and the focus has been on strong winds under conditions of neutral thermal stability. Note that spectra can be presented in dimensionless or dimensional forms (the latter will be used here) where the latter has units of $(m/s)^2$/Hz. An alternative way of presenting information is via descriptions of the scales (in the three orthogonal directions) of turbulence, where the scales represent the sizes of the larger eddies, as could be identified in Figure 1. Knowledge of the scales and the wind speed give an alternative method of describing the frequency content. Such data are also given in ESDU.

A dimensional energy spectrum of the turbulent along-wind velocity encompassing a wide frequency range is shown in Figure 7. Data were obtained in strong winds from the Brookhaven National Laboratory, via anemometers which were located in relatively rough terrain (z_0 ~ 1 m) at approximately 100m from the ground. Whilst data are for a specific location, the authors note that the spectra from other locations exhibit similar spectral gaps and amplitudes. Four distinct peaks can be seen in the spectrum. They include three peaks at very low frequencies which can be considered as quasi-static for aircraft, since the relative size of aircraft is small compared with the wavelengths. Of relevance is the peak at the right hand end. It is separated from the longer-term diurnal and weather effects by a “spectral gap” centred at a period of about 30 minutes, suggesting that a one-hour average will capture turbulence effects in the boundary layer well and may exclude the longer-term influences. Quoted values of turbulence intensities are commonly measured over 30 minute to an hour, and if longer term influences are present in the data they are removed by filtering or similar techniques, thus quoted values of intensities do not include the energy existing at longer timescales.

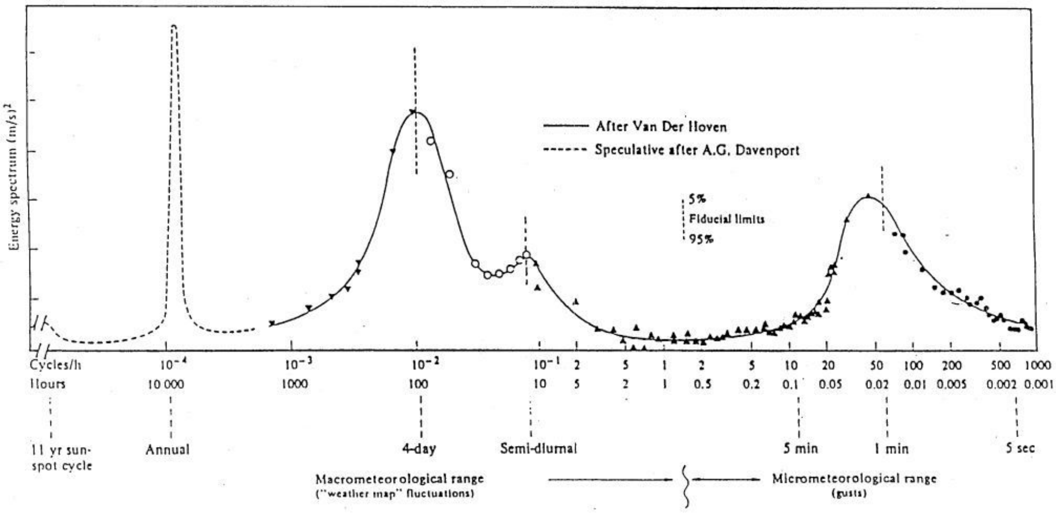


Figure 7 Spectrum of turbulence at 100m [24]

3 Turbulence experienced by aircraft moving through the ABL

The relative turbulence intensity for an aircraft flying through the ABL is given by the standard deviation of the atmospheric velocity fluctuation (in the direction of flight) divided by the IAS. The effect of moving through the turbulence at a velocity that is significantly higher than the mean wind speed is to reduce the relative turbulence intensities (i.e. as perceived by the moving vehicle) and relative fluctuating flow angles, and generally to increase the frequencies experienced. This relative turbulence intensity is denoted by *J* and for the along-flight direction is:

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

The addition of the mean vehicle speed V_{Veh} (i.e. with reference to the Earth, rather than the wind) does not change the magnitude of turbulence fluctuations in the numerator, but it does increase the mean relative velocity in the denominator, thus reducing the perceived turbulence levels. When an aircraft is stationary with respect to the ground (for example a fixed wing aircraft on a runway or a hovering rotary wing craft) this reduces simply to I_u since there is no speed relative to the ground and IAS is simply the mean wind speed - and thus is the same as used by the wind engineers for buildings. An example of the effect of increasing IAS is shown in Figure 8. It should be noted that I_u can vary considerably with terrain and elevation and can be selected from Figure 6.

Aircraft can move through the turbulence at any angle relative to the mean wind axis thus they can experience a mix of the three orthogonal turbulence components. Resolving the fluctuating components in the atmospheric wind into directions parallel and normal to the relative flight direction enables prediction of the relative intensities experienced. This has been investigated for road vehicles [7] where it was found that the highest values of relative turbulence intensity were for the headwind and tailwind cases and a similar conclusion can be drawn for an aircraft flying in straight and level flight. There are also differences in the spectra for u, v and w which vary with elevation. Details can be found in the ESDU data sheets but are not considered further here.

As an example consider the relative turbulence levels impinging on the wing of a large commercial aircraft taking off from an airport with roughness length z_0 = 0.1 m. Assume the wing is 5m from the ground and there is a 20 m/s headwind. From Figure 6 the turbulence intensity I_u will be about 0.24 when the aircraft is stationary. As the aircraft moves forward the IAS increases to a takeoff speed of 80 m/s (thus giving a groundspeed of 60 m/s) at which point J_u / I_u falls to about 0.26, which gives a relative turbulence intensity of 0.062. For a tailwind the relative turbulence intensity will remain the same but the takeoff groundspeed will be 100 m/s. Note that for very smooth terrains I_u can be lower than 10% but the mean windspeed close to the ground will be higher whereas for city centres with many high-rise buildings I_u can be over 50% but with a lower mean windspeed. It is also relevant to note that the effects of local wakes can augment the relative turbulence intensity [7].

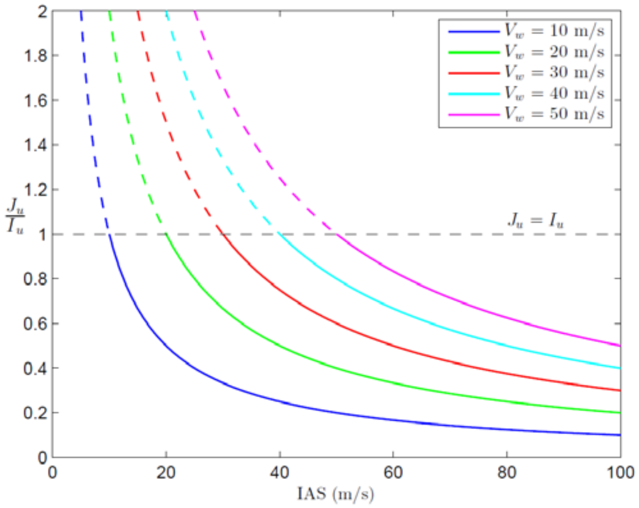


Figure 8 The influence of increasing ground speed on relative turbulence intensity

4 Recent dedicated measurements for MAV research

Measurement of turbulence characteristics have recently been made as part of a program dedicated to understanding the MAV turbulent flight environment. The measurements were taken a few metres above the ground in various terrains, where it was envisaged MAVs would most likely operate, and are relevant to commercial aircraft during their takeoff and landing phases. Measurements were made during the day under conditions of nominally neutral stability, where the turbulence arose from mechanical mixing of the flow rather than being thermally driven. As details of the instrumentation and procedures used have already been published[1], only an overview will be given here.

Four dynamically calibrated TFI[2] Cobra pressure probes were used (for details of probes see [30-33]). Inter-probe lateral separations could be varied from 14 to 150 mm, thus covering MAV virtual wingspans of 42 mm to 450 mm. Multi-hole pressure probes were used because they provide a more robust alternative to hot-wire anemometers (HWA) and, via a dynamic calibration, have a frequency response that is flat from 0 to greater than 2,000 Hz. The probes were able to resolve the three orthogonal components of velocity and static pressure, as long as the flow vector was contained within a cone of ±45° around the probe x-axis. This enabled resolution of the constantly fluctuating velocity vector in turbulent flow when the probe was approximately aligned with the freestream flow direction and the turbulence intensities were not excessively large (typically below 30%, which was the case for most of the measurements except in very built up terrain). The particular probes used for these measurements had 2.5 kPa (0.3 psi) pressure transducers, and were dynamically calibrated by the manufacturer to allow accurate flow measurements up to ~50 m/s.

Three series of tests have been carried out using this instrumentation; in the first the probe heads were mounted 3.9 m from the ground, on a mast above a vehicle, and aligned nominally to the direction of motion, see Figure 9. A wide variety of terrains and conditions were surveyed using vehicle speeds from 0 to over 20 m/s.

[1] Downloadable from http://mams.rmit.edu.au/cibbi0b6g34o.pdf

[2] Turbulent Flow Instrumentation, see www.turbulentflow.com.au

Figure 9 Test vehicle with probe system (inset) and schematic of single head (above)

The second and third series of tests were made using only ground-based measurements on telescopic masts. For the second series of tests z = 2m and z_0 ~ 0.05 m and for the third z = 10 m and z_0 ~ 1.0 m. A large volume of data was recorded and only selected portions are presented here.

Selected longitudinal spectra are presented in Figs. 10 to 11 for a range of atmospheric wind speeds, an elevation of 3.9 m, and various terrains. In most cases several spectra obtained under nominally similar conditions (identified by similar colours) are shown on each figure.

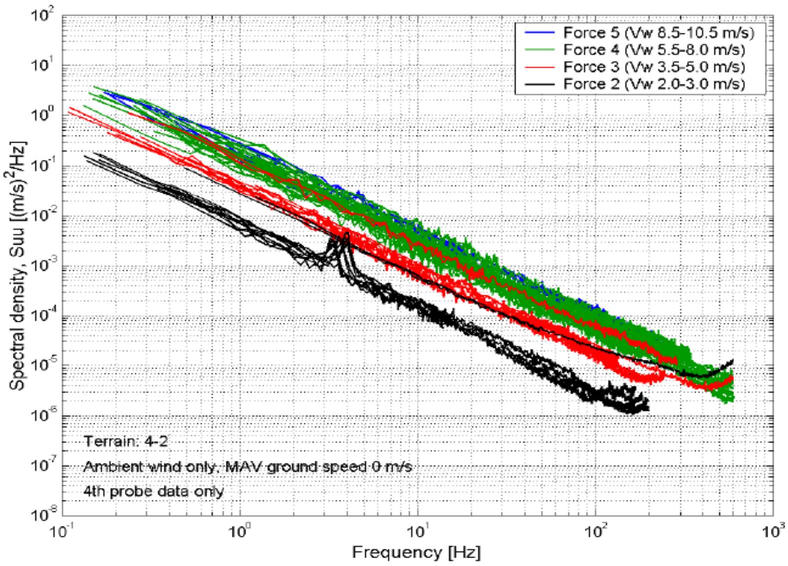


Figure 10 Atmospheric u-component spectral levels for different wind speeds, ISO terrain 4,
z_0 ~ 0.10 m (three different locations ambient wind only, i.e. MAV effective ground speed 0 m/s).

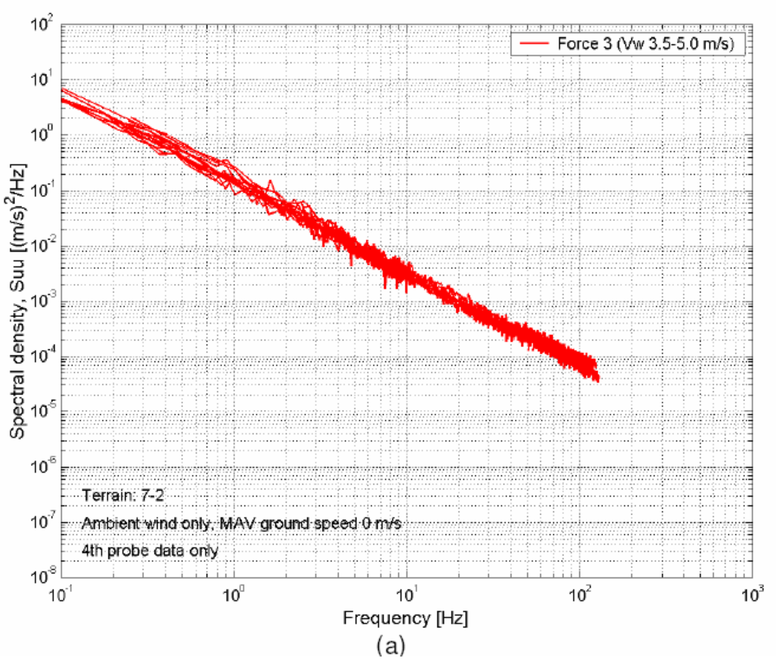


Figure 11 Atmospheric u-component spectral levels, ISO terrain 7, z_0 ~ 1.0 m: ambient wind only.

Figure 10 illustrates the spectral content for a relatively wide range of atmospheric winds. Note that the data obtained for the lowest level (Force 2) were obtained in initial experiments; the small peak in the spectra is due to a resonance in the dynamics of the car/probe system which was rectified with an improved mounting system and did not occur in further tests. The spectra cover the frequencies from 0.1 to 100 Hz and thus just the higher frequency parts of the more complete atmospheric spectrum given in Figure 7. It is clear that the shape of all spectra are closely similar and that for the given frequency range they follow the well-known 5/3rds Kolmogorov spectral decay. When a flight velocity is imposed on the data there will be a shift of the spectra. If similar wind speeds are considered, but in a rougher terrain, the spectra show a higher level of energy; i.e. contrast the (red) force 3 lines in Figure 10 with Figure 11.

5 Physical replication of turbulence for aircraft in wind tunnels

5.1 Introduction

Wind engineering wind-tunnel studies generally replicate the mean shear in the ABL as well as replicating other turbulence characteristics in model scale tests, since the loadings on tall, slender buildings and towers are very dependent on the variation of the atmospheric wind with elevation. For aircraft the time-averaged shear in the vertical direction may be far less significant, since wings are relatively thin and are nominally horizontal. Thus it seems reasonable to generate profiles of time-averaged velocity and turbulence statistics that are invariant in the vertical and horizontal directions to study the primary effects of turbulence. This then ignores the effect of the ground on the turbulence (i.e. as the ground is approached the vertical velocity components in the atmosphere reduce to zero) and also raises the issue of the influence of the other boundaries on the flow (i.e. walls of a wind-tunnel and CFD boundaries).

Bi-planar grids perpendicular to the flow are commonly used to generate nominally homogeneous turbulence across the tunnel test section in wind studies. These are usually positioned at the test section entrance, rather than being placed further upstream in the contraction, since contractions reduce the turbulence intensities. The reduction of intensity is directly related to the contraction ratio, thus the high levels of contraction ratios used in conventional aeronautical wind tunnels will greatly reduce the level of generated turbulence intensity when grids are placed in settling chambers. In order for sufficient mixing to occur the test location needs to be many grid dimensions downstream of the grid location (typically 10-20) and the intensity decays with increasing distance from the grid. These considerations lead to the requirement of long test sections and testing in decaying turbulence intensity, which is generally not the case outdoors unless the terrain roughness is varying. The scales of turbulence are directly related to the scale of the grid members. When replicating ABL turbulence it is usually desirable to generate as large as possible scales in order to get a good match between a model characteristic length scale (for instance wing chord) and turbulence scale. This requires large grids and tests sections with long development lengths as are normally used in wind engineering wind tunnels. Active methods have been employed to try to increase the scales of turbulence for a given size of test facility since ABL turbulence scales are typically tens of metres in dimension. Active methods can increase the scales slightly; albeit at considerable complexity and a review can be found [34]. In building aerodynamics, which has had a long history of replicating ABL turbulence in wind tunnels, Reynolds number scaling is usually not achieved (and is usually orders of magnitudes lower than full-size). This lack of dynamic similarity is generally disregarded as the ABL flows are highly turbulent and often relatively sharp-edged geometries (i.e. rectangular section buildings) are being considered. For commercial aircraft this is not the case and unless very small aircraft are being tested, or much reduced scale models are being utilized, it is unlikely that a 1:1 scaling between aircraft and turbulence scales will be possible. An exception to this is dynamic testing of MAVs and low Reynolds number airfoils where it is possible to get reasonably good scaling between characteristic dimensions and relevant turbulence scales and intensities at correct Reynolds numbers [35].

5.2 Experience from MAV testing

A series of experiments have been conducted to understand the influence of ABL turbulence on the dynamics and control of MAVs (via flying experiments in replicated ABL turbulence in a large wind tunnel) and the time-averaged performance of airfoils (via force and pressure measurements) [12]. Grid-generated turbulence levels were varied from nominally smooth flow up to about 0.12 in the longitudinal direction. Relatively few tests have been conducted where the influence of turbulence intensity and scale has been independently evaluated. However the effects can be significant at low Reynolds numbers [36]. The effects of turbulence intensity and scale on time-averaged and time-varying airfoil characteristics at higher Reynolds numbers remain relatively unexplored. This is currently an area of interest for wind turbine applications as well as for aircraft flying through the ABL.

6 Concluding remarks

The range of turbulence characteristics experienced by aircraft is wide and depends upon the flight speed and the atmospheric wind speed, as well as terrain, elevation, and the stability of the atmosphere. The highest levels of turbulence will be experienced under the highest atmospheric wind speeds permissible for takeoff or landing, which will be aircraft specific. Under these strong wind conditions it is likely that the stability of the atmosphere will be neutral and the large database of turbulence characteristics from meteorological and wind engineering measurements can be utilized to find the turbulence characteristics for any given altitude and terrain roughness from a fixed frame of reference. It is then relatively simple to calculate the relative turbulence intensities as a function of IAS. The turbulence scales and/or spectra can also be obtained from the same reference sources. However a very wide range of frequencies are inherent in atmospheric turbulence and some will be so large they can be considered as quasi-static. This will depend upon the scale of the aircraft and the problem being considered. Scales of turbulence similar to the characteristic dimensions of micro aircraft will be influential for the overall perturbations of such aircraft yet will be far less consequential for the overall perturbations of large passenger craft - but will perturb the boundary layers. Conversely the larger scales of atmospheric turbulence will give rise to large perturbations of passenger craft but could be considered as quasi-static to micro aircraft.

If the effects of atmospheric turbulence are to be studied by physical replication it is clear that scale will be a limiting factor – for micro aircraft generating relevant scales can be achieved in relatively large wind tunnels via standard methods (such as upstream grids) and thus correct Reynolds number scaling can also be achieved, since the full-sized MAV craft can be studied. However for large aircraft this is not feasible due to the size of facilities that would be required. Whilst active turbulence generation schemes are sometimes used to increase the scales in wind engineering studies the enhancement of the scales are modest. To study the effects of turbulence on passenger aircraft reduced scaling techniques would have to be used (as is commonplace in wind engineering studies) but Reynolds number similarity would be compromised.

Acknowledgments

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