A REAL-TIME ATMOSPHERIC TURBULENCE MODEL
FOR AIRCRAFT FLIGHT SIMULATORS

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Abstract

The purpose of this paper is to demonstrate a computationally efficient method of providing realistic atmospheric turbulence data that can easily be incorporated into a flight simulator. The turbulence data is derived from the SNLWIND-3D program, which is based on a Monte Carlo approach. Although the SNLWIND-3D code was originally developed for use with wind turbine design and analysis methods, the turbulence data that is generated by the code can readily be adapted and used to develop an atmospheric turbulence model for use within a flight simulator system as described later in this paper. The new turbulence model will soon be a key element of the Navy Pioneer unmanned aerial vehicle training simulator. This simulator is now used for training Navy pilots at DOD UAV Training Center (DUTC), Ft. Huachuca, AZ.

Introduction

In 1994 the USA Army Corps of Engineers, Construction Engineering Research Laboratory (CERL), was awarded the initial contract by the Army to develop a flight simulator. The purpose of the flight simulator was to aid in the training of pilots, coaching them to pilot the Pioneer unmanned aerial vehicle (UAV) from Army LPD carrier ships and, in particular, hone their skills at landing the UAV into the capture net on the carrier deck. This effort continues, and the task of managing the development of the simulator has since been moved to the Naval Command, Control and Ocean Surveillance Center (NCCOSC) RDTE, San Diego, CA. The refinement of the model in the simulator is ongoing, including the atmospheric turbulence model.

One of the more difficult problems faced during the development of a flight simulator is to provide realistic atmospheric mean wind and turbulence data. For the current work, the turbulence model should accurately reflect the turbulence characteristics (conditions) over the ocean, near and around the carrier ship, as well as land-based landing conditions. Most previous turbulence models account only for two-dimensional gusts. A robust turbulence model should account for all three gust components and also include swirl effects. The current approach (based on a three-dimensional Monte Carlo atmospheric turbulence simulation) correctly simulates the point-to-point correlation of three-dimensional gusts, both laterally (spanwise) and longitudinally (lengthwise). Thus, effects such as longitudinal swirl that can cause an aircraft to roll abruptly were incorporated into the turbulence model. Videotaped footage of several landing approaches showed that swirl gusts lead unexpected

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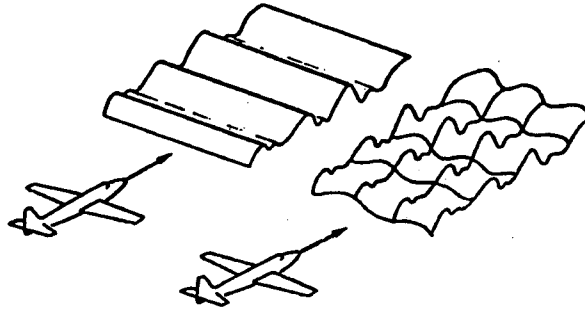
Fig. 1   Spanwise uniform turbulence vs. random or nonuniform turbulence in all directions (taken from Ref. 8).

Fig. 2   Typical gust distributions over an aircraft wind producing vertical "bumps," rolling and/or yawing momentums (taken from Ref. 8).

rolling motions that can veer the UAV off course. As a result, pilots are often faced with difficult and complex situations in which they have to return the UAV to the correct flight path or risk damage to the aircraft. For the untrained or inexperienced pilots these conditions can be daunting. Pilot reactions should become second nature. It is therefore important that the swirl components be incorporated into the turbulence model. Integration of the new turbulence model into the Pioneer flight simulator has therefore lead to a more realistic simulation of three-dimensional atmospheric turbulence.

A Brief Overview of Turbulence and Gust Models and Their Application

Extensive research has been done on the characteristics of gusts, turbulence and mean wind. The classic report by Barr, Gangaas and Schaeffer[1] contains (1) a comprehensive description of the characteristics of turbulence, gusts and shear, (2) various turbulence models, (3) methods for incorporating turbulence into a simulator and (4) the effects of turbulence on an aircraft. This reference been used extensively by many researchers to extract data, derive methods for implementation, and validate turbulence characteristics.

In other research, Flomenhoft[2] discusses the application of gust models to calculate the load factor on aircraft structures. Flomenhoft mentions that Wagner[3] laid the foundations for modern unsteady aerodynamics, which was later extended by Jones[4] to include wings of finite aspect ratio. Wagner developed a lift-lag function, which was used by Küssner[5] and applied to the entry of an aircraft into gusts. Küssner derived the solution of an aircraft's response in the vertical plane, assuming no
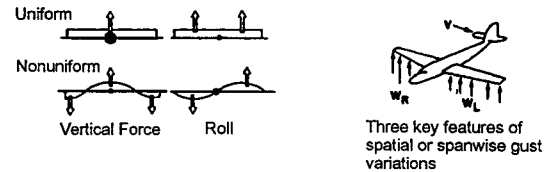
pitching, for sharp-edged gusts with linear gradients and maximum velocity peaks. However, Rode and Lundquist[6] published several years before a paper dealing with the load factor experienced by an aircraft flying from calm air into a gust oriented normal to the flight path. It was concluded that sharper edged gusts do not adequately represent the effect of gusts on very heavy nor very light aircraft. The ANC-1 Flight Loads subcommittee of the NACA began work to better define and describe gust entities and analysis. (Note: ANC stood for Air Force-Navy-Civil.) Two models were proposed (to improve upon the sharp-edged gust formulation), one was a half-cycle sine function, and the second a 1-minus-cosine function. The latter was selected because it had no discontinuity at time zero. Using this new gust function, the response of an aircraft in the vertical plane was determined and a new gust alleviation factor computed—more accurately.

In later years, the NACA published several reports describing the atmosphere in terms of power spectra of gust velocities and the corresponding flight vehicle responses to them. Power-spectral techniques later became the basis for analyzing and predicting gusts and gust loads, including models such as the von Kármán and Dryden models.

Camp[7] et al. described that turbulence models commonly used for analysis and simulation purposes typically are random in the flight direction but uniform in the spanwise direction. He noted that a more realistic situation should be chosen in which the turbulence is considered to be random in both the flight and spanwise directions, as shown in Fig. 1. Using a uniform gust field along the span of an aircraft does not yield an accurate representation. This is especially true for aircraft with larger wing spans. Care should be taken to pick a turbulence model that will render accurate representation of the turbulence and its effect on the corresponding aircraft. Also, two distinct types of gusts can be found

over an aircraft wing at any point in time, each with varying intensity, as depicted in Fig. 2. The first type is a uniform gust loading, which typically will result in primarily a vertical force. The second is a non-uniform gust loading that can result in either a vertical force with or without an associated aircraft rolling moment.

Etkin,[8] in studies on turbulent wind and gusts and their effects on flight, described turbulent wind to consist of discrete gusts and continuous turbulence. Discrete gusts are considered isolated encounters with steep gradients, which have evolved from the sharp-edged step function, used during the earlier days of aviation, to the 1-minus-cosine function. Random turbulence describes the continuous chaotic motion of air, which should include statistical features such as stationary homogeneity, isotropy, time and distance scales, probability distributions, correlations and spectra. It is also important to model turbulence characteristics with respect to altitude, in which turbulence intensity decreases with an increase in altitude. Several factors should be considered in modeling the atmospheric boundary layer. The mean wind is governed by surface roughness and turbulence intensities in the surface layer (lower than 10% of the boundary layer) are unequal for each of the three wind components. These intensities are a function of surface roughness. Above the ground boundary layer, the differences in intensity of each component decrease and tend to equal out outside the boundary layer.

Most flight simulator applications typically use filtered white noise shaped to either a von Kármán or Dryden spectrum, in one or more of the wind/turbulence axes. However, pilots flying these flight simulators complain that the turbulence models do not feel like "real" turbulence. Quoted from Etkin[8], this can be attributed to several potential deficiencies of this approach:

(1) The pitching, rolling, and yawing about the respective axes, associated with the swirl components (q_g, p_g, and r_g) are absent.

(2) The Gaussian distribution is unrealistic—the "intermittency" and "patchiness", surprise element characteristic of real turbulence, is missing.

(3) In simulations of landing through the boundary layer, the inhomogeneous nature of turbulence needs to be reflected in a statistically non-stationary process for the airplane.

(4) Anisotrophy and boundary-layer shear both lead to the inputs [of the turbulence model] being altitude dependent. Moreover, shear has the additional effect of influencing the basic stability of small perturbations, which should also be included in the simulation if high fidelity is sought.

(5) Since wind and turbulence are related to an Earth-fixed axis, the components on vehicle axes depend on heading relative to the wind and on the angles of pitch, roll, and yaw.

It is argued, from the above mentioned points, that using time recorded data for the turbulence model of a flight simulator would be favorable.

In yet another paper, Campbell[9] discussed several methods of incorporating turbulence models in flight simulators, including a "frozen" turbulence database created using the Monte Carlo simulation method. A three-dimensional block of turbulence data for each gust component was generated in advance. The frozen turbulence data was generated in such a way that the length scale could vary in an arbitrary fashion, i.e. the turbulence was non-dimensionalized. With dimensional turbulence data the block changes size with length scale; whereas with dimensionless the block has constant volume. Due to the limited volume of the turbulence block it was necessary to fill the flight simulator environment by stacking the environment with the smaller turbulence blocks. Two methods were suggested to fill the simulator environment. The first was to stack copies of the same block in the same orientation to fill the total simulator domain. The second method was to stack each successive block with its own mirror image—laterally and longitudinally. The second method avoided the problem of discontinuities at the edges of each the frozen turbulence blocks. At the time this model was presented, no cross-spectral information was contained in the turbulence model and it was not sure how to add it either. Nonetheless, the resulting wind and turbulence was non-linear and non-Gaussian. Lastly, Campbell[10] mentions that the most consistently observed characteristics of atmospheric turbulence is the power spectral density falloff with frequency to the -5/3 power.

Categories of Turbulence Models Used In Flight Simulators

There are several methods of incorporating turbulence models in flight simulator systems, each of which have their respective pros and cons. Reeves[11] has outlined four general approaches to providing atmospheric turbulence, which are as follows:

(1) One method is to record real turbulence data over a time period and store the information. During execution of the flight simulator system, the recorded data is recalled. It cannot be argued that this method will provide very realistic data. This method, however, is limited to the time duration (length) and physical grid size used for taking the data. Other problems include the restriction of changes in altitude or different atmospheric conditions, and physical limitations of the size of the recorded data and storage capacity and speed of data access (e.g. disk I/O) during flight simulator runtime.

(2) Another method is to randomly generate mean wind and turbulence data upon request. Although in some sense this method is less limiting, it is restricted by the implementation of the random-function itself, which is used to "randomly" generate atmospheric turbulence data. Most random-functions use a predefined algorithm to produce the data. The data, however, is far from being random and is most likely to have some statistical predictability and repeatability.

(3) Some work has been done on using multiple (ten or even more) sine wave generators and summing the results to produce turbulence. This method would result in turbulence that is generated with a fixed phase. No apparent advantages can be seen in using this method, and there are no obvious relationships between the fixed-phase generators and the randomness of atmospheric turbulence.

(4) Another method—probably the most commonly used—involves using filtered white noise. This approach involves generating turbulence by filtering Gaussian white noise and amplifying the signal to match the required spectrum and RMS intensity. Most turbulence features can be generated in this way after suitable manipulation of the results. Unfortunately, turbulence is not a Gaussian process, and thus this model is incomplete as it cannot reproduce the non-Gaussian nature of turbulence.

The approach taken in this paper was to use a combination of the first two methods fused into a single hybrid method. Using this approach, several turbulence data files can be generated, in advance, for each of the different conditions that are expected to be encountered within the flight envelope and simulation environment, thus giving several advantages.

Based upon the characteristics mentioned in the previous sections, it was decided to employ a pseudo-frozen turbulence model that was non-Gaussian and contained proper cross-spectral relationships. Since a simplified turbulence model would be inadequate (which assumes a uniform gust distribution spanwise), there was a need for a turbulence model that could provide a random gust distribution over the span and length of the aircraft. Moreover, it was required that all three gust components be included. Most of the criteria were satisfied by the SNLWIND-3D code,[12] to be described in the following sections.

In a paper by Frost[13] various turbulence models are discussed. Frost mentions the typical indicial function which gives the lift response of a wing due to a sinusoidal gust occurring at a fixed position along the wing. A second approach mentioned was to use a strip theory with gust gradient data, i.e. finite elements along the span of the wing. The advantage to this method is that a random distribution of data along the wing can be used, and independent yawing and rolling moments can be calculated. The last turbulence model that Frost suggests is imposing three-dimensional small scales of turbulent motion into the JAWS data set. Frost states that the last method is highly complex and suggests using the second method or a hybrid of the second and third method.

Finally, in another paper by Frost[14] several methods are discussed how to incorporate a turbulence model into a flight simulator system. One method in particular that is mentioned is that of a "corridor" data set using "frozen" turbulence. Frost mentions that this may be a good idea but that older computers might not have enough storage capacity. However, with more modern computers found today this is not a problem any more.

Application of the SNLWIND-3D Code

SNLWIND (also known as the "Sandia" method) was the original numerical turbulence simulation code developed by Veers[15] for atmospheric turbine simulations for use in wind turbine system dynamics codes. In the Sandia method, a time history of actual turbulence was recorded, and functions were developed to numerically simulate these characteristics, using a Fourier synthesis. The SNLWIND simulation generates a full spatial distribution of the time-varying streamwise wind component producing several points in a plane perpendicular to the mean wind. The model propagates a time series in the mean wind direction at the mean wind speed using Taylor's frozen turbulence hypothesis. This "full field" method completely fills a 3-D block space with a grid of instantaneous wind speeds, as sketched in
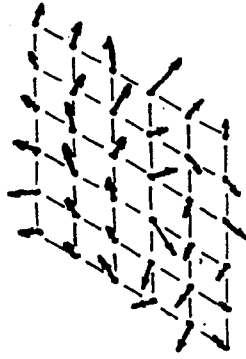
Fig. 3   3-D block in plane perpendicular to the mean wind.

Fig. 3.

Measurements and comparisons were done by Kelley and Wright[16] against the original Sandia method, and it was found that it simulated atmospheric turbulence quite realistically. Unfortunately the SNLWIND code only simulated the longitudinal component (u) of the wind. The original SNLWIND code was further refined to include all three components (u, v, and w) of the turbulent wind vector, and also to simulate characteristics of turbulent wind fields upwind and downwind of wind farms (sites with arrays of wind turbines for electric power generation), as well as over a uniform flat terrain. The new and refined code is now called SNLWIND-3D. Models were developed for the velocity variance spectra, spatial coherence, and cross-axis component correlations. These realistically reflect the statistical characteristics of true turbulence.

Two versions of the SNLWIND-3D code were acquired for this work. The first version produces turbulence data in the three components (u, v, and w) that include the mean wind. The second produces turbulence data that reflect only the fluctuating turbulence components u', v', and w'. It was decided to test both versions. Turbulence data was generated for the flight simulator, one set of data included only the fluctuating turbulence components, and the other set included the mean wind. After careful scrutiny of the turbulence data and their effect within the flight simulator, it was decided to use the data that contained only the fluctuating turbulence components.

Several parameters in the SNLWIND-3D code can be changed to produce varying levels of turbulence
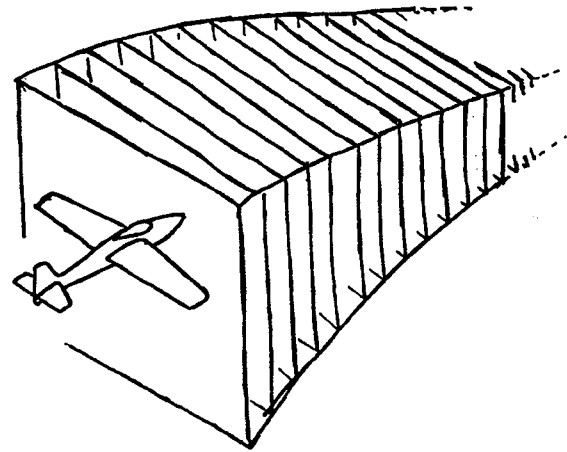

Fig. 4   Aircraft flying through pseudo-frozen turbulence "tunnel" made up of a multitude of grids that are aligned perpendicular to the aircraft longitudinal axis and parallel to the ground.

intensity with different turbulence models. The parameters include specifying the spectral turbulence model (ranging from a homogenous terrain, a rougher homogenous terrain, a very turbulent model, IEC Kaimal model, or IEC von Kármán model), surface roughness, the atmospheric model, power law coefficient, and several more. As an example, to simulate conditions over low sea state, the "smooth" turbulence model would be used with a surface roughness of about 0.001 m and a neutral atmosphere. To simulate small-scale coherent structures in the flow, the spectral model would be changed to "internal" with a turbine row-to-row spacing of 7D, and a slightly positive stability ($+0.005 \leq$ Ri No $\leq +0.040$), with a small roughness length of around 0.005 m.

Data Reduction and Implementation

SNLWIND-3D generates turbulence data for a given time period, which by default is 10 minutes with a time step or interval of 0.05 sec. Using this data and the mean wind speed, the time-dependent data is converted to spatial data resulting in a pseudo-frozen turbulence model in relative Cartesian coordinate format. (What is meant by "pseudo-frozen turbulence" is described later.) The pseudo-frozen turbulence model uses an 6 x 6 grid (similar to the 3-D block as shown in Fig. 4) with 12,000 grid elements within the "tunnel". There is a spacing of 2.077 ft (0.633 m) between each grid. The spacing between each point on the grid is 4 m (13.1 ft) giving a
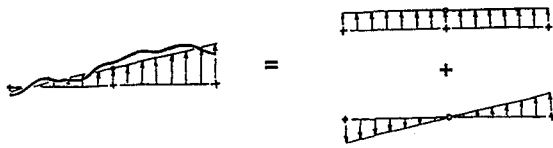
Fig. 5   Data reduction method: using a least squares method to fit a linear line through the points along the wing. The y-intercept represents the gust and the slop represents the swirl.

grid dimension of 20 m x 20 m (65.6 ft x 65.6 ft). The grid covers an effective area of approximately 25,000 ft (7,620 m) in length, as shown in Fig. 4. The SNLWIND-3D code was used to generate various turbulence data files for use within the simulator. Each associated with respective levels of turbulence intensity, terrain conditions, and altitude variations. Each of these data files are assigned predetermined names representing the different flight conditions and turbulence models. During the execution of flight simulator, the turbulence conditions can be changed simply by loading the appropriate data file.

Rather than stacking several frozen turbulence blocks side-by-side to fill the simulation environment, it was decided to continuously align the turbulence block lengthwise (parallel) with respect to the x-axis of the aircraft. There are two reasons for doing this. First, the way in which the turbulence data was originally recorded and from which the mathematical models were developed were such that the u-component was always aligned with respect to the mean wind direction, i.e. longitudinal. Second, this method reduces computational overhead and allows the simulator to run at higher real-time frequencies. Only the u-component of the turbulence and the x-axis of the aircraft are kept aligned, the aircraft can rotate about its x and y-axis (roll and pitch). For reference, the u, v and w turbulence components provided by the code correspond to the x, y (out left wing) and z (up) axes.
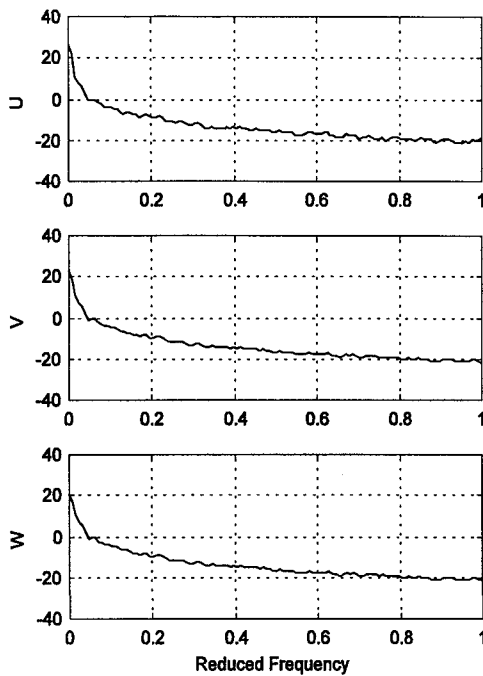
As the aircraft flies through the atmosphere, in the simulator, its absolute displacement is calculated relative to its previous position. A new position for the aircraft is calculated within the pseudo-frozen turbulence "tunnel" and is also oriented by rotating it through the roll and pitch angles. A predetermined number of points along the aircraft wing are used to calculate the turbulence
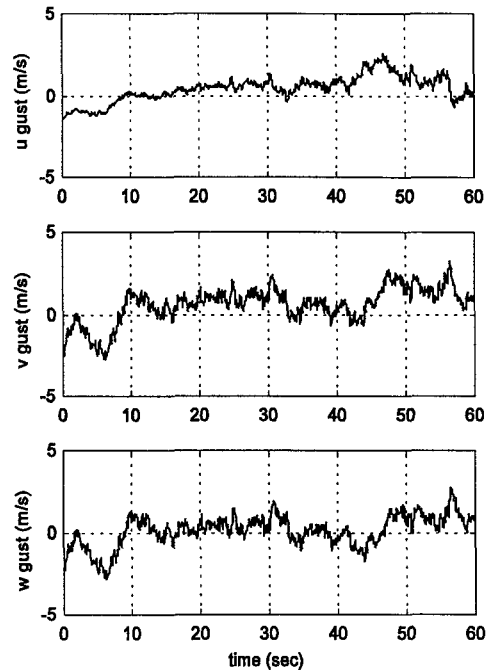
Fig. 6   U, V and W gust components displayed for the first 60 seconds. The data was generated from the "smooth" turbulence model at a height of 25 m above the ground.

values for each point, by linear interpolation, for each of the turbulence components. Next, a least squares method is used to fit a linear line through the turbulence points (over the wing). The resulting slope value is used to calculate the swirl component and the y-intercept is used to determine the gust component, for each of the three turbulence components, as shown in Fig. 5.

The flight simulator code initially obtains values of the current state variables from wind tunnel data and computations using six degree of freedom model (6-DOF). The current state variables that are used to compute the successive stages are the body velocity components, the body angle rate components, the inertial position components (the simulator makes use of the North-East-Down model for defining the coordinate system) and the angular orientation in quaternion components. The computation of the successive stages are made by using the Runge-Kutta fourth-order integral,
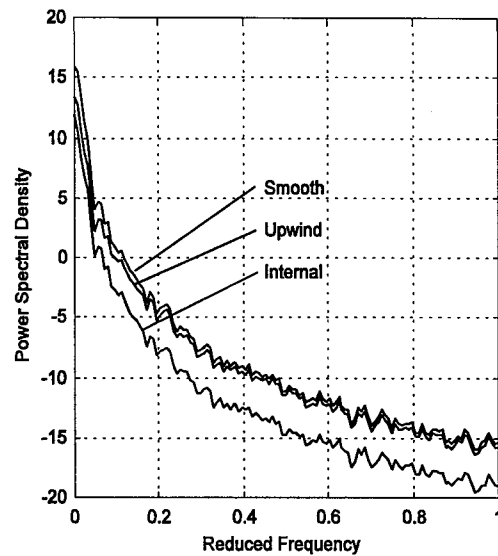
Fig. 7 Power Spectral Density (PSD) plots for the u, v and w gust components.

Fig. 8 Spectral density plots for comparison of the "smooth," "upwind" and "internal" turbulence models produced by the SNLWIND-3D code.

which computes the derivatives of the current state variables. At each stage the new set of Aerodynamic coefficients (C_L, $C_{L\alpha}$, etc) is calculated using the component buildup method. Using these coefficients the force and moment values are updated and used to compute the derivatives of the current state variables. These derivatives are used to calculate the new current state variables.

The gust and swirl components of velocity obtained from the turbulence code were incorporated into the flight simulator code at each time step. At each integral step the gust (u_g, v_g, w_g) and swirl components (p_g, q_g, r_g) the turbulence was added to the body velocity components (u, v, w) and the angular velocity components (p, q, r) respectively to obtain the resultant velocity components. These are further used to compute the new state variables as described before.

Turbulence Data Validation

To validate the data it is important to look at various parameters and characteristics of the gust components and their effect on flight. Figure 6 shows a time series plot for the u, v, and w gust components for a 1 minute (60 secs.) interval, and Fig. 7 shows the corresponding power spectral density (PSD) plots with a reduced frequency scale. The spectral density for the turbulence was calculated using the Welch method for spectral estimation and a Hanning window. The data for the figures was generated using the SNLWIND-3D program at a specified height of 25 m above the ground, in conditions simulating that over an ocean as given in Table 1. Figs. 6 and 7 show that the u, v and w components are independent from each other and also the spectral density is in agreement with the papers referenced in the previous sections.

SNLWIND-3D can generate turbulence data with varying degrees of intensity. As discussed earlier, three main models are provided. These are "smooth," "upwind" and "internal," each with increasing turbulence intensity. Fig. 8 shows the spectral density plots for each of these models.

Examining Fig. 9 reveals the typical gust shape and

characteristics as generated by the code. The time scale is relative, measured in 1/100 of a second, showing 1.2 seconds of data. At the beginning of the gust there is a sharp and dramatic rise in the gust velocity, which has a short plateau and more gradual deceleration to a state where the gust velocity is more or less equal that of the mean wind.

Figure 10 shows the w gust component and PSD plots, using the same "smooth" turbulence intensity model, at height levels of 25, 100 and 200 m above the ground (varying the "*mean flight level*" and "*height of reference wind speed*" parameters). As can bee seen from the plots, the gust intensity reduces with altitude. Close to the ground the turbulence level is high, which is typically caused by coherent structures within wind path and other contributing factors such as boundary layer shear. Also, Table 2 shows the average wind speed at different flight levels based on a center grid mean wind speed of 13 m/s for each height. As the height above ground level is increased the wind gradient decreases, as expected. Table 2 shows the wind gradient is particularly
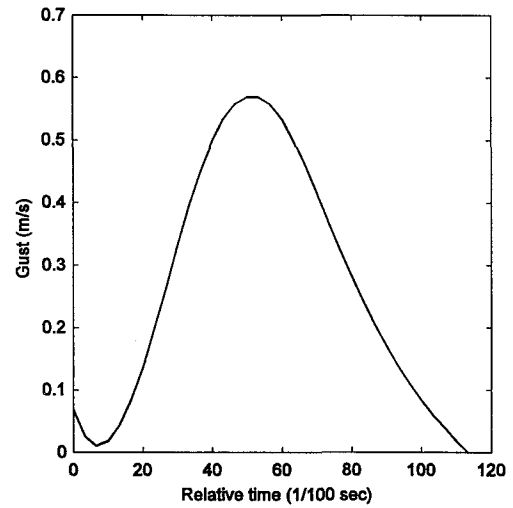

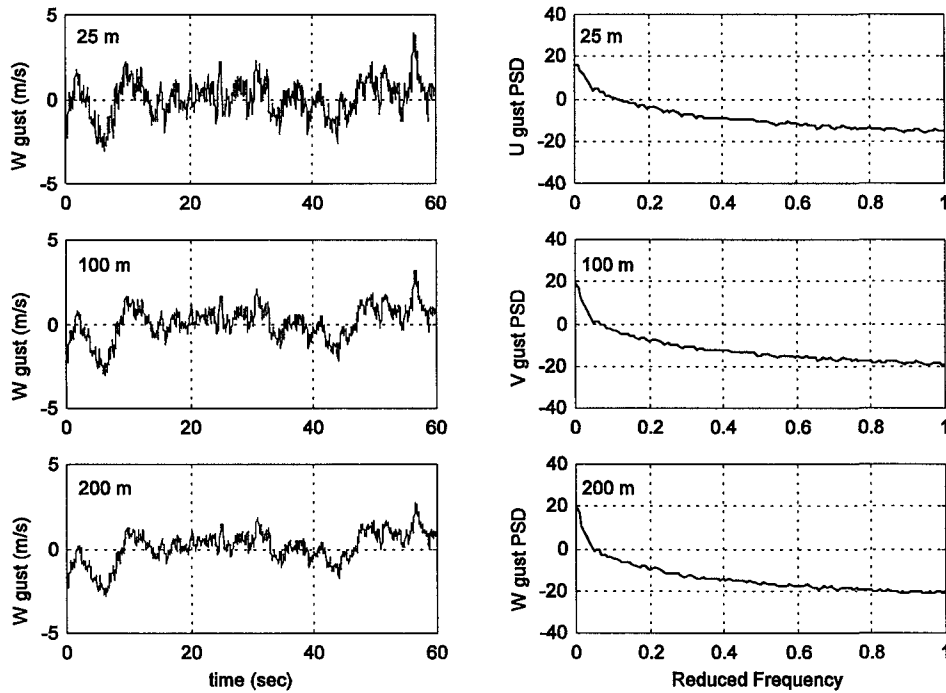**Fig. 9   Typical shape of a gust for the w-component (vertical).**

Fig. 10   Comparison of turbulence levels at different height levels 0f 25 m, 100 m and 200 m.

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strong just above the ground at 25 m, and while still within the earth boundary layer (but almost out of it, close to the edge) the wind gradient is negligible at 200 m.

Lastly, Fig. 11 (displayed after references) shows a time-series plot of an aircraft wing flying through the turbulence grid. The wing span is normalized. The dotted line represents the wing, and each of the triangles represent a fixed location over the wing (fixed along the span). The computed gust intensity at the spanwise location is represented by the relative height above the wing centerline. A line is fitted through these individual gust points. The fitted line is represented by the dash-dot line. The y-intersect value represents the gust, indicated by the thick solid line at relative wing location 0, and the slope of the line represents the swirl component. In the case shown the swirl is very minimal.

Conclusions & Summary

Using the turbulence data generated by SNLWIND-3D code it was possible to generate and use a pseudo-frozen turbulence grid that included all of the characteristics desired. This included separating the turbulence from the mean wind from each of the components (where needed), a mean wind that fluctuates with time, the ability to simulate wind shear and boundary layer effects, low sea state conditions, and small scale coherent structures. The SNLWIND-3D code allows for the specification of the turbulence intensity level, and simulate proper point to point cross correlations between the individual components.

Acknowledgments
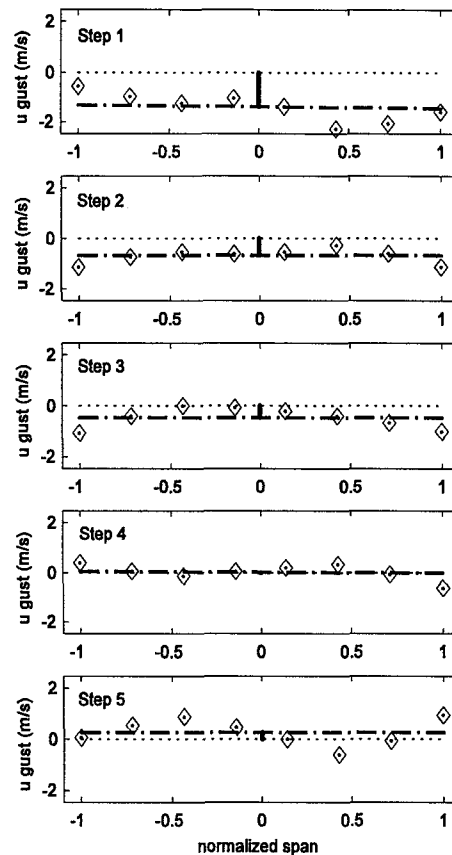
Fig. 11 Time-step sequence (1 sec interval) showing aircraft wing and non-uniform gust vectors across the span. The linear least-squares fitted line is used to calculate the gust (y-intersect) and swirl (slope) components.

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Table 1. Parameters and values of input file to simulate turbulence conditions over the ocean, using the "smooth" turbulence model and fluctuating components only.

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 ----    | ffield-3D CARTESIAN INPUT PARAMETER FILE FOR NO MEAN VERSION
 ----    | --------------------------------------------------------
 ----    | TURBINE/MODEL SPECIFICATIONS ...
 ----    | --------------------------------------------------------
    6    | SQUARE GRID POINT MATRIX DIMENSION (EVEN VALUES ONLY)
 0.05    | TIME STEP (SECONDS)
10.00    | LENGTH OF TIME SERIES (MINUTES)
    1    | NUMBER OF BLOCKS TO BE SIMULATED
 25.0    | MEAN FLIGHT-LEVEL, ZHUB (M)
20.00    | MAX GRID DIMENSION, RDIAM (M)
 ----    | --------------------------------------------------------
 ----    | METEOROLOGICAL BOUNDARY CONDITIONS ...
 ----    | --------------------------------------------------------
SMOOTH   | TURBULENCE MODEL: SMOOTH,UPWIND,INTRNL,IECKAI,IECVKM
   NA    | TURBINE ROW-TO-ROW SPACING FOR INTRNL MODEL ONLY (7/14)
 30.0    | HEIGHT OF REFERENCE WIND SPEED, UREF (M)
13.00    | MEAN WIND SPEED AT REFERENCE HEIGHT, ZREF (M/S)
0.000    | GRADIENT RICHARDSON NUMBER, RI_NO
0.001    | SURFACE ROUGHNESS LENGTH, Z0 (M)
0.143    | POWER LAW EXPONENT, PLEXP
0.000    | FRICTION OR SHEAR VELOCITY, USTAR (M/S)
0.000    | MIXING LAYER DEPTH, ZI (M)
(default)| u'w' CROSS-CORRELATION COEFFICIENT, PC_UW, (0.000)
(default)| u'v' CROSS-CORRELATION COEFFICIENT, PC_UV  (0.000)
(default)| v'w' CROSS-CORRELATION COEFFICIENT, PC_VW  (0.000)
0.000    | U COMPONENT COHERENCE DECREMENT, COHD_U
0.000    | V COMPONENT COHERENCE DECREMENT, COHD_V
0.000    | W COMPONENT COHERENCE DECREMENT, COHD_W
 0.25    | COHERENCE EXPONENT, COHEXP
 ----    | --------------------------------------------------------
 ----    | RUNTIME OPTIONS:
 ----    | --------------------------------------------------------
1251022  | RANDOM SEED, ISEED (BETWEEN 0 AND 2147483647)
z5.bin   | THE ENDING OF THE H MATRIX FILES TO BE READ OR DEFINED
   NO    | USE A PREVIOUSLY DEFINED H MATRIX? YES-NO
   NO    | CREATE TIME SERIES FILES? YES-NO
 _cmp    | TIME SERIES FILE NAME SUFFIX (IGNORED IF PREV OPT='NO')
```

Table 2. Wind gradient at various flight levels for the upper and lower edges of the 20 m x 20 m grid.

Grid Location	Flight Level Height		
	25 m	100 m	200 m
Upper (+10 m)	13.29	13.09	13.04
Lower (-10 m)	11.71	12.71	12.86
Difference	**1.58**	**0.38**	**0.18**