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HELICOPTER-V/STOL DYNAMIC WIND
AND TURBULENCE DESIGN METHODOLOGY

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INTRODUCTION

Aircraft and helicopter accidents due to severe dynamic wind and turbulence continue to present challenging design problems. The development of the current set of analysis tools for aircraft wind and turbulence design began in the 1940's and 1950's and remains today a developing field. The areas of helicopter dynamic wind and turbulence modeling and vehicle response to severe dynamic wind inputs (microburst type phenomena) during takeoff and landing remain as major unsolved design problems from a lack of both environmental data and computational methodology.

This paper will review the development of helicopter and V/STOL dynamic wind and turbulence response computation methodology, outline the current state of the design art in industry, and comment on design methodology which may serve to improve future flight vehicle designs.

DIFFERENCES BETWEEN AIRCRAFT, V/STOL, AND HELICOPTERS

A review of recent literature provides an interesting comparison of V/STOL, helicopter, and aircraft flight characteristics and design methodology. Gust response of helicopters with lifting rotors, rotary-fixed wing aircraft, and large diameter propellers in V/STOL and tilt rotor aircraft is discussed in [1]. He notes that the major difference between conventional aircraft and rotary wing-propeller gust wind response modeling in forward flight is that even with stationary turbulence velocity input to rotor blades, the resultant vehicle response is nonstationary because of the gust front encounter with blades at various azimuth positions.

Thus, even the simplest gust statistical analysis for the rotary wing vehicle is fundamentally nonstationary and substantially more complex to analyze than a comparable aircraft problem. Gaonkar points out that three criteria establish feasibility of the nonstationary problem analysis as follows:

1. Taylor's hypothesis holds.
2. Gust fluctuations are Gaussian although nonstationary.
3. Helicopter rotor gust excitations can be idealized as a separable nonstationary process composed of a conventional stationary gust field modulated by the deterministic rotor transfer characteristics.

For the case of hovering helicopters, Lakshmikantham and Rao [2] computed rotor blade turbulence response utilizing conventional linear, stationary turbulence theory. Computational results were obtained for hinged and wingless rotors.

Judd and Newman [3] analyzed helicopter rotor response to gusts and turbulence and concluded that current articulated and semi-rigid rotors are insensitive to in-plane gusts. Vertical gust sensitivity is relatively independent of forward speed and inversely proportional to blade loading (not disk loading), whereas aircraft gust sensitivity is proportional to forward speed and inversely proportional to wing loading.

Reichert and Rade [4] concluded that helicopters, with their relatively low disk loading, are sensitive to gusts when compared with aircraft; that disk loading is the major design parameter affecting turbulence; and that gust-induced structural loads are less important for design than maneuver-induced gusts.

In 1972, Elderkin et al. [5] noted in the TOLCAT report that both aircraft and V/STOL flying at high velocity and moving in the direction of the mean wind see atmospheric turbulence modeled by

$$\left. \frac{\partial u_i}{\partial t} \right|_a \approx -U_a \frac{\partial u_i}{\partial x_j}$$

with the aid of Taylor's hypothesis (the variation of turbulence seen by the aircraft is linearly related to the variation of turbulence in the longitudinal direction). However, the hovering helicopter sees a turbulent eddy motion which satisfies

$$\left. \frac{\partial u_i}{\partial t} \right|_a = -u_j \frac{\partial u_i}{\partial x_j} - \frac{1}{\rho} \frac{p}{x_i} - r \frac{\partial^2 u_i}{\partial x_k \partial x_k} + g \frac{\theta}{\theta} \delta i_3.$$

Here the turbulence seen by the aircraft is related to spatial turbulence in a nonlinear manner. Thus, the helicopter in hovering or slow-speed flight presents a significantly different analysis-modeling problem.

In 1982, Azuma and Saito [6] studied rotor gust response using local momentum theory and concluded that unsteady aerodynamics are not a significant factor, that rotor blade bending effects are significant and attenuate the gust load factor as opposed to aircraft where structural flexibility amplifies response, and that rotor gust response is not sensitive to Lock number,

$$\gamma = acR^4/I.$$

The V/STOL aircraft, when compared to the helicopter, has relatively small aerodynamic forces during approach and hover. In general, the control of a V/STOL vehicle at slow speed is very dependent on the propulsion system.

Etkin [7] noted several important differences between conventional aircraft and STOL/VTOL vehicles as follows: STOL/VTOL aircraft fly steeper descent paths, the lower flight path speeds accentuate the flight path response to turbulence and shear, and nonstationary statistical analysis methods must be used.

REVIEW OF HELICOPTER--V/STOL TURBULENCE MODEL DEVELOPMENT

It is interesting to review the development of Helicopter--V/STOL turbulence models with special emphasis on wind and turbulence spatial shear and flight dynamics model turbulence--wind input modeling. Basically, statistical gust models and analysis methods are considered because of their applicability to precise flight vehicle response to a random environment. Many important studies are not mentioned in the following discussion and references are chosen to illustrate a few stops along the path of design method evolutionary development.

Summers [8] conducted a flight test experiment using an instrumented B-26 as a probe to measure gust power spectra for

$$u_g, v_g, w_g, \frac{\partial w_g}{\partial y}, \text{ and } \partial u_g / \partial y.$$

He formulated the measurement problem to include effects of spanwise horizontal and vertical gust effects on the aircraft. Gust velocities were defined relative to quasi-internal axes moving with CG mean motion. He assumed that

$$\frac{\partial w_g}{\partial y} \approx p_g \quad \text{and} \quad \frac{\partial u_g}{\partial y} \approx r_g$$

i.e., the assumption of small aircraft size relative to the gust eddy vortex size. The same basic formulation continues today.

In 1968, Skelton [9] conducted the first comprehensive V/STOL wind and gust model theoretical analysis and simulation. One objective of study was to recommend that TOLCAT experiments aimed at basic low-altitude V/STOL wind-turbulence model data acquisition. A few of the accomplishments of the study include: (a) development of a theoretical gust model formulation for V/STOL aircraft in sideways or forward motion; and (b) a simple derivation of turbulence component (spatial) cross-correlations for isotropic turbulence. He derived the set of three-dimensional, spatial, non-zero cross-correlations which exist in isotropic turbulence due to wind shear as shown in Figure 1.

Skelton formulated TOLCAT experiment requirements for low-altitude wind and turbulence measurement, such as: (a) measurement of gust spectra at very low frequencies to define the wind-gust demarcation frequency; (b) measurement of joint probability densities for the mean wind amplitude, friction velocity, and gradient Richardson number as a function of altitude; and (c) seven more experiment definitions.

Elderkin [5] and others conducted perhaps most significant, classic V/STOL-helicopter-oriented low-altitude wind and turbulence model study. A few of the study accomplishments and limitations are as follows:

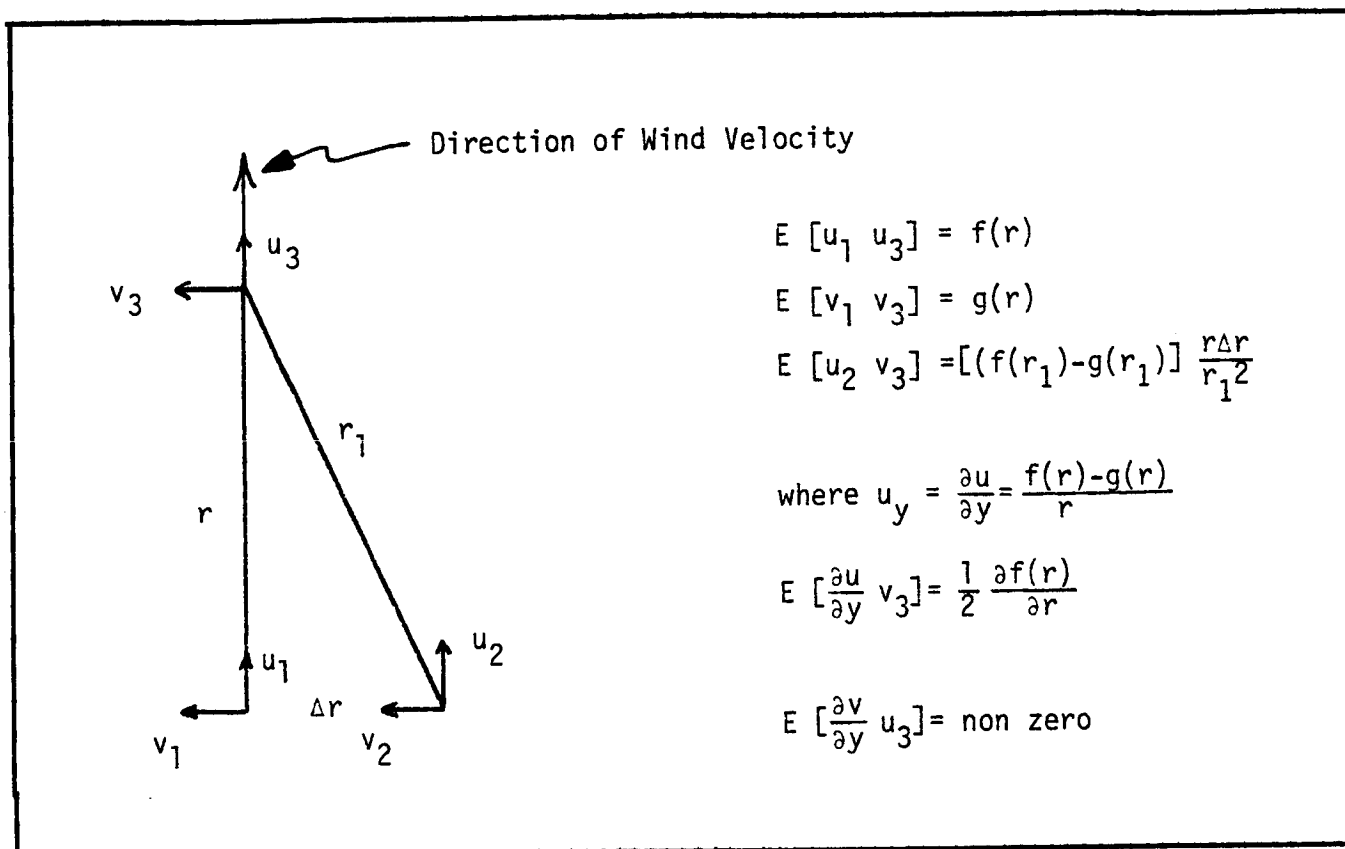


Figure 1. Non-Zero Cross-Correlations Which Exist in Isotropic Turbulence.

- A. Individual and joint probability density functions were measured for all turbulence components. Power spectra were obtained by Fast Fourier Transform.
- B. The spatial aspects of turbulence structure were studied along with the relationship between the temporal and spatial domains. Taylor's hypothesis was investigated and verified.
- C. The theoretical analyses by Skelton [9] and Elderkin [5] are complete enough to furnish a sound basis for analysis of the data acquired.
- D. Experimental data covered the lowest 200 feet of the atmosphere.
- E. Taylor's hypothesis was verified for eddy sizes less than 10 times the height of the aircraft.
- F. Spatial data may be translated to aircraft flight only for aircraft flying in the wind direction.

Schaeffer [10] reported on an FAA study of wind models for flight simulator certification of landing and approach guidance and control systems. The significant aspects of the study are as follows:

- A. Developed a wind model in $h < 1000$ feet.
- B. Reviewed atmospheric turbulence modeling theory.
- C. Transformed turbulence components from each axis to aircraft body axis.
- D. Defined effective turbulence angular velocities in the same sense as Summers [8] and Skelton [9] to account for spatial wind gradients.
- E. Proposed a wind-turbulence model for automatic landing certification.

All of the above wind and gust models basically utilize model mean wind characteristics and isotropic-homogeneous gust turbulence. A second approach to wind modeling evolved in parallel to the stationary gust models. NASA launch vehicle design for winds aloft and gust response utilized nonstationary statistical analysis methodology, synthesized deterministic wind profiles based on winds aloft statistics, and used Monte Carlo simulation of vehicle responses utilizing winds aloft data.

In 1967, Bailey, Palmer and Wheeler [11] synthesized a wind aloft model shaping filter for both wind and turbulence. Nonstationary shaping filter differential equation coefficients were derived with multiple linear regression techniques. The model was utilized to determine launch vehicle response characteristics by the nonstationary statistical adjoint method. This planar analysis is now well formulated in higher dimension utilizing a matrix formulation. The nonstationary statistical approach is perhaps the most applicable methodology for solution and simulation of the dynamic wind (wind shear).

problem. The above analysis followed the work of Bieber [12].

Tatum et al. [13] developed a nonrecursive turbulence model for simulation of space shuttle ascent trajectories. One-dimensional gusts and gust gradients are developed from three-dimensional von Karman spectra, integrated over the flight vehicle dimensions. Digital filter theory was utilized to develop a nonrecursive discrete shaping filter for Monte Carlo turbulence velocity generation. This analysis method generated time series of both linear gust velocities and gust gradients (u_1, u_2, u_3)

$$\partial u_2 / \partial x_1, \partial u_3 / \partial x_1, \partial u_3 / \partial x_2, \text{ and } \partial u_1 / \partial x_2$$

for tape storage and future playback. The resultant analysis methods utilized a different approach from that of Etkin [7], but both methods included first order effects of wind shear.

Smith and Lambert [14] developed a synthetic wind profile based on properties of the quadrivariate normal probability distribution function for Kennedy Space Center winds aloft. The deterministic wind design profile was utilized to determine ascent loads for the space shuttle. The synthetic vector wind profile (SVWP) is formed as the distribution of wind shears which varies with the mean wind vector at a reference height, altitude, month, and launch site. The 99% conditional shears are used in the SVWP. The concept of synthetic wind profiles for design has been developed by NASA for the Apollo and Shuttle programs. The method by Smith provides some theoretical justification for the SVWP choice.

The preceding references on wind and gust modeling basically outline the necessary methodology to establish fundamental design wind and turbulence models for microburst type events. Model formats which may be postulated are as follows:

1. Synthetic microburst profile based on nonstationary statistical analysis of wind shear event data.
2. Nonstationary Statistical Model based on current data available.

The resultant model format could evolve based on a three-dimensional jet model or by brute-force statistical analysis of available microburst data.

Analysis techniques and methodology applicable to the microburst-type events seem to be well developed. Model development should be straightforward when an event data base is well developed. The basic data is probably available for hover turbulence model specification. However, further analytical method development is necessary to input the gust velocities realistically into the rotorcraft flight dynamics mathematical model.

During the preparation of this paper, three helicopter manufacturers were surveyed as to their wind and gust modeling design methodology. They typically used both discrete and continuous gust models for design and simulation. The primary deficiencies in industry practices today seem to be lack

of a good hover turbulence model and inadequate design inputs for microburst-type wind events.

Two high-time helicopter instructor pilots were interviewed as to their perception of microburst-type dynamic wind events. They were aware of the problem and had seen U. S. Army and FAA material on the subject. Neither pilot had encountered a microburst event although both pilots agreed that on both takeoff and landing, under heavily loaded conditions, wind events with high shear could be a problem for helicopters.

CONCLUSIONS

In general, wind and turbulence modeling for helicopters and V/STOL rotorcraft is more complex than for conventional aircraft. The state-of-the-art for wind and turbulence model application to rotary-wing and V/STOL aircraft is not well developed and several notable gaps exist, such as lack of verified gust models for the hover case. Basic rotor blade turbulence response theory is currently evolving in the scientific literature for the general rotorcraft dynamic response case. Several conclusions that may be stated from this rather quick look at the rotorcraft--V/STOL dynamic wind and turbulence design problem are as follows:

1. Dynamic wind response of aircraft and rotorcraft in forward flight may be analyzed by similar techniques. Wind and turbulence models which suffice for aircraft analysis requirements will likely meet rotorcraft design requirements for high-speed forward flight.
2. Helicopter, rotary wing V/STOL, and propulsion-dominated V/STOL aircraft during transition and hover flight present a very different set of requirements on the wind model. Hover turbulence models can probably be formulated from existing data bases but much work remains for rotorcraft applications.
3. In general, modeling methodology and concepts have changed little over the past 30 years. Primarily, refinements have been added to wind and turbulence models conceived in the 1950's. Wind and turbulence spanwise and chordwise effects on the aircraft are well approximated by both historical and current modeling methodology.
4. Techniques developed by NASA for modeling launch vehicle wind aloft response seem directly applicable to the microburst phenomenon. Nonstationary statistical models present no major problems when used in conjunction with manned simulations. Modern digital technology simplifies generation of nonstationary wind and turbulence time series. Analysis of piloted simulator results for nonstationary events is more difficult.
5. The synthetic wind profile concept is a definite contender for both vehicle design (control system and structural) and piloted simulator training.

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