Investigation of the Influence of Simulated Turbulence on Handling Qualities

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Pilot opinion of the handling quality of a light general aviation aircraft was evaluated in a simulated turbulence environment. The turbulence is described in terms of rms intensity and scale length and their variation with time. Significant changes in pilot opinion ratings were obtained with variation in turbulence models and these are discussed in terms of complexity and suitability for handling-quality studies.

Introduction

THIS paper presents the results of an investigation of simulator turbulence models on pilot handling-quality evaluations. It is important to evaluate handling qualities and ride qualities in the presence of turbulence. Several methods have been used to generate turbulence; each on aimed at realizing the actual atmospheric turbulence as closely as possible. A realistic representation of turbulence becomes especially important in simulation of future aircraft with high sensitivity to turbulence, as even light to moderate turbulence may seriously degrade their controllability and ride quality.

This work is part of an overall program to establish a realistic model of atmospheric turbulence which is easily implemented in flight simulator studies to investigate the interacting effects of turbulence on aircraft ride and handling qualities. Several atmospheric turbulence models have been tested and evaluated, with a pilot in the loop, in terms of realism, frequency content, relative amplitude of aircraft disturbances, patchy characteristics, element of surprise, and aircraft handling-quality ratings.

In this paper it will be demonstrated that the handling quality (Cooper-Harper) rating[1] is a function of the composition of the simulated turbulence in addition to the turbulence intensity (rms values). Several other characteristics of turbulence field such as realism, frequency content, etc., have also been found to be a function of the manner in which the turbulence is created.

Description of Turbulence Disturbances

Several presently used turbulence simulation techniques are described in Ref. 2 and their properties reviewed from the standpoint of realism, frequency content, patch characteristics, and the element of surprise to a pilot. The classical method, most widely used for turbulence simulation, is the linearly-filtered white noise technique. The resultant signal is shaped so that the power spectrum and the intensities match those of real turbulence. A Dryden or Von Karman form is normally used to model the power spectrum. The Dryden model is remarkably easy to implement on simulators and can be adjusted for any general power spectrum. However, this model (Gaussian) fails to exhibit the non-Gaussian patchy characteristic of real atmospheric turbulence.[3]

In this program, four basic models are tested on the NASA/Langley Research Center's Visual Motion Simulator (Fig. 1): 1) Gaussian Model; 2) Modified Gaussian Model; 3) Rayleigh Model; and 4) UVA Turbulence Model.

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Gaussian Model

The Gaussian Model described in the preceding is tested on the simulator to establish a basis of comparison. The Dryden form of power spectral density ϕ and the linear filter $G(s)$ used in this model are given by

$$\phi_u(\omega) = \sigma_u^2\left(\frac{2L_u}{\pi V_0}\right)\left(\frac{1}{1+(L_u\omega/V_0)^2}\right) \tag{1}$$

$$\phi_v(\omega) = \sigma_v^2\frac{L_v}{\pi V_0}\left(\frac{1+3(L_v\omega/V_0)^2}{[1+(L_v\omega/V_0)^2]^2}\right) \tag{2}$$

$$\phi_w(\omega) = \sigma_w^2\frac{L_w}{\pi V_0}\left(\frac{1+3(L_w\omega/V_0)^2}{[1+(L_w\omega/V_0)^2]^2}\right) \tag{3}$$

$$G_u(s) = \sigma_u\sqrt{\frac{2}{\pi\phi_0}\left(\frac{V_0}{L_u}\right)}\left[\frac{1}{s+(V_0/L_u)}\right] \tag{4}$$

$$G_v(s) = \sigma_v\sqrt{\frac{3}{\pi\phi_0}\left(\frac{V_0}{L_v}\right)}\left[\frac{s+\frac{1}{\sqrt{3}}(V_0/L_u)}{[s+(V_0/L_u)^2]^2}\right] \tag{5}$$

$$G_w(s) = \sigma_w\sqrt{\frac{3}{\pi\phi_0}\left(\frac{V_0}{L_w}\right)}\left[\frac{s+\frac{1}{\sqrt{3}}(V_0/L_w)}{[s+(V_0/L_w)]^2}\right] \tag{6}$$

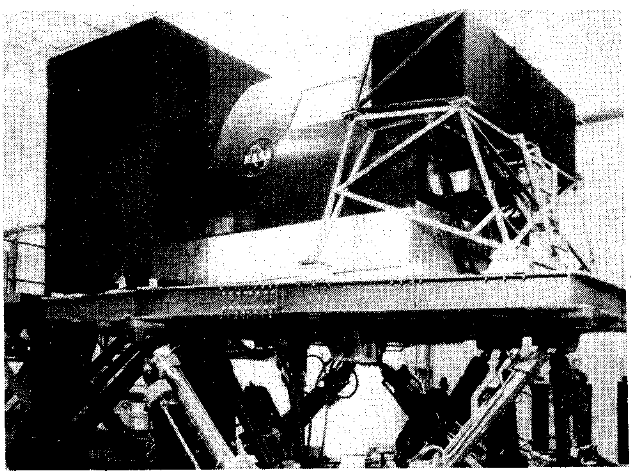

Fig. 1 The Visual Motion Simulator (VMS) at the NASA Langley Research Center.

where V_0 is the initial total velocity; ϕ_0 the white noise source; ω the frequency; L_i the scale for turbulence velocities; σ_i the rms turbulence intensities; and i a subscript denoting the u, v, w components.

The scale lengths for this model are computed from

$$L_u = L_v = L_w = 1750 \text{ ft } (533.4 \text{ m}) \quad \text{for } h \geq 1750 \text{ ft } (533.4 \text{ m}) \tag{7a}$$

$$L_u = L_v = 145(h)^{1/3} \quad \text{for } h < 1750 \text{ ft } (533.4 \text{ m}) \tag{7b}$$

and

$$L_w = h \tag{7c}$$

where h is the altitude.

Modified Gaussian Model

The Modified Gaussian Model is obtained by altering the Dryden linear filter $G(s)$ (see Fig. 2) to include random variations of rms intensity, by use of a random number generator passed through a distribution modifier. Time histories are then generated by passing Gaussian white noise ϕ_0 through the linear filter modified by the distribution modifier.

The non-Gaussian patchy nature of atmospheric turbulence suggests that the field is composed of two components: one to represent the variation of intensity within a patch and the other to represent variations of intensity with time. The distribution modifier in this model essentially represents the variation of intensity with time. The level of turbulence within each patch is controlled by the magnitude of the rms intensity.

The distribution modifier is the probability density function of the rms intensity. Analysis of several sets of atmospheric turbulence data characterized by various atmospheric conditions shows that a truncated Gaussian distribution best fits the probability density of rms intensity.[4] In this test program two sets of data characterized by terrain, altitude, and atmospheric stability are used (see Table 1). The turbulence field generated by using these distribution modifiers will be referred to as Model 2 and Model 3 (Model 1 is the Gaussian Model).

Rayleigh Model

The Rayleigh Model is derived from the Modified Gaussian Model by replacing the distribution modifier by a Rayleigh probability density function. The Rayleigh probability density function for rms vertical turbulence intensity σ_ω is given by

$$P(\sigma_\omega) = (\sigma_\omega / C^2) \exp(-\tfrac{1}{2}\sigma_\omega^2 / C^2)$$

where C^2 is one-half the expected value of σ_ω^2.

From the Dryden spectrum models of real atmospheric turbulence, the value of C has been estimated in Ref. 5 to be 2.3 fps (0.7 m/sec). The rms intensities of the longitudinal u and the lateral v gust components are obtained from the relation: $\sigma_u^2/L_u = \sigma_v^2/L_v = \sigma_w^2/L_w$, with scale lengths given by Eqs. (7). This model will be referred to as Model 4.

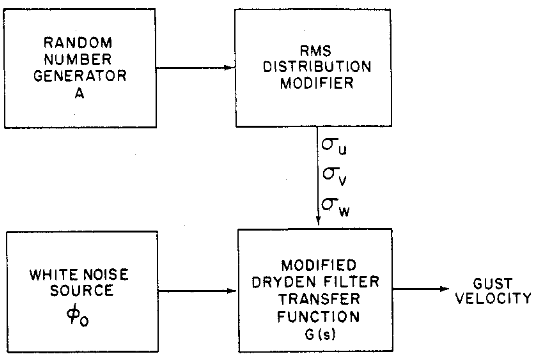

Fig. 2 Modified Gaussian turbulence simulation.

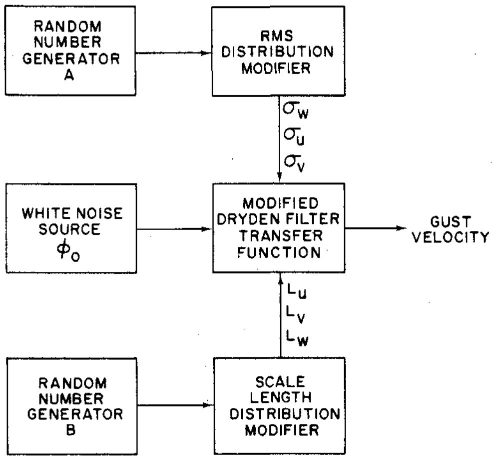

Fig. 3 UVA gust model turbulence simulation.

UVA Turbulence Model

The UVA Turbulence Model includes, in addition to the rms distribution modifier, a scale length modifier. A block diagram of this model is presented in Fig. 3. In addition to controlling the patchiness of the turbulence field, the time variation of scale length achieves numerical compatibility with real atmosphere and further randomizes the simulation.

The scale length distribution modifier is derived from data collected in the LO-CO CAT Program[4] for various combinations of altitude, terrain, stability, temperature, and geographic location. Reference 2 presents the Gaussian distribution of scale length for two atmospheric conditions characterized by altitude, terrain, and stability. Table 2 presents the mean and variance of the scale length distribution modifier. The two atmospheric conditions tested will be referred to as Model 5 and Model 6.

Table 1 Distribution modifiers

		Mean	Variance
rms Distribution modifier Model 2			
Altitude: 250 ft (76.2 m)	σ_u fps (m/sec)	3.1 (0.94)	1.2 (0.37)
Atmospheric stability: Unstable	σ_v fps (m/sec)	3.2 (0.97)	1.2 (0.37)
Terrain: Plains	σ_w fps (m/sec)	2.8 (0.85)	0.9 (0.27)
rms Distribution modifier Model 3			
Altitude: 750 ft (228.6 m)	σ_u fps (m/sec)	3.2 (0.97)	0.8 (0.24)
Atmospheric stability: Unstable	σ_v fps (m/sec)	3.5 (1.07)	1.0 (0.30)
Terrain: Mountain	σ_w fps (m/sec)	4.1 (1.25)	0.9 (0.27)

Table 2 Distribution modifiers

		Mean	Variance
rms Distribution modifier Model 5			
Altitude: 250 ft (76.2 m)	σ_u fps (m/sec)	3.1 (0.94)	1.2 (0.37)
Atmospheric stability: Unstable	σ_v fps (m/sec)	3.2 (0.97)	1.2 (0.37)
Terrain: Plains	σ_w fps (m/sec)	2.8 (0.85)	0.9 (0.27)
	L_u ft (m)	415 (126.4)	110 (33.5)
Scale length modifier	L_v ft (m)	325 (99.1)	86.6 (26.4)
Model 5	L_w ft (m)	335 (102.1)	83.1 (25.3)
rms Distribution modifier Model 6			
Altitude: 750 ft (228.6 m)	σ_u fps (m/sec)	3.2 (0.97)	0.8 (0.24)
Atmospheric stability: Unstable	σ_v fps (m/sec)	3.5 (1.07)	1.0 (0.30
Terrain: Mountains	σ_w fps (m/sec)	4.1 (1.25)	0.9 (0.27)
	L_u ft (m)	415 (126.4)	116.5 (35.5)
Scale length modifier	L_v ft (m)	460 (140.2)	126.6 (38.6)
Model 6	L_w ft (m)	425 (129.5)	132.9 (40.5)

Table 3 Input-output intensities

Model no.	Input rms fps (m/sec) u	v	w	Output rms fps (m/sec) u	v	w
1	4.0 (1.31)	4.0 (1.31)	4.5 (1.37)	3.97 (1.21)	3.90 (1.19)	4.43 (1.35)
2	m[a] = 3.1 (0.94) v[b] = 1.2 (0.37)	m = 3.2 (0.97) v = 1.3 (0.37)	m = 2.8 (0.85) v = 0.9 (0.27)	3.92 (1.19)	3.53 (1.07)	2.6 (0.70)
3	m = 3.2 (0.97) v = 0.8 (0.24)	m = 3.5 (1.07) v = 1.0 (0.30)	m = 4.1 (1.25) v = 0.9 (0.27)	3.90 (1.19)	3.90 (1.19)	3.80 (1.16)
4	m = 6.1 (1.86)	m = 6.1 (1.86)	m = 6.1 (1.86)	5.19 (1.58)	4.84 (1.47)	4.48 (1.36)
5	m = 3.1 (0.94) v = 1.2 (0.37)	m = 3.2 (0.97) v = 1.2 (0.37)	m = 2.8 (0.85) v = 0.9 (0.27)	3.60 (1.09)	3.5 (1.07)	2.60 (0.79)
6	m = 3.2 (0.97) v = 0.8 (0.24)	m = 3.5 (1.07) v = 1.0 (0.30)	m = 4.1 (1.25) v = 0.9 (0.27)	3.60 (1.09)	3.92 (1.19)	3.82 (1.16)

[a] m - mean. [b] v - variance.

The theoretical results of the turbulence field generated by each of the six models is presented in Ref. 2. The statistical analysis is presented in the form of: 1) mean and standard deviation; 2) normalized fourth and sixth moments; 3) probability density functions; 4) power spectral densities; 5) patchiness; and 6) frequency of element of surprise. The results, where possible, are compared with the real atmospheric turbulence.

Test Program

The six-degree-of-freedom Visual Motion Simulator (VMS) at the NASA/Langley Research Center was employed to simulate the Canadian deHavilland DHC-6 Twin Otter. The VMS is a motion-based simulator with the basic interior and instrumentation of a jet transport cockpit. The Twin Otter was chosen for simulation because it is a typical STOL aircraft and its flying characteristics are well-known. In addition, there are many pilots available with flying experience in the Twin Otter to validate the simulation.

Seven pilots experienced in civil, military, and research flying were used in the program. Test runs, each of 8- to 10-minute duration, for each of the six simulated turbulence models were made in one pilot session. During separate sessions, some of the pilots repeated the six test cases in a random order. It was decided to have the pilots fly in a level flight constant altitude tracking task in order not to introduce too many variables that might distract the pilots from their primary objective of trying to distinguish differences between various turbulence models. After each run the pilot was asked for his comment on the turbulence by means of a flight questionnaire. The flight questionnaire asked the pilot to estimate the turbulence intensity, realism, relative amplitude of aircraft motion, patchiness, work load, task performance, and the Cooper-Harper Rating for the airplane-turbulence interaction. Additonal questions tried to find why the pilot did or did not find turbulence realistic, whether the turbulence was too continuous or too patchy, and whether the motion contained annoying amounts of high or low frequencies. In addition, the pilots were also asked to estimate the altitude, terrain, and the atmospheric stability in relation to his flying experience in turbulence.

Several aircraft parameters, such as pitch, roll, yaw and normal acceleration were recorded on strip charts for further analysis.

The rms intensity of the longitudinal, lateral, and vertical gust field is presented in Table 3. The output intensity (rms) is the statistical analysis of a 10-min sample of the gust field.

Results of Simulation

Data obtained during the flight test program consisted of pilot opinion ratings and commentary relating to the simulated turbulence environment and the aircraft handling qualities and data relating to the physical environment to which the pilot was exposed. Pilot opinion and ratings have

Table 4 Handling-quality ratings

	Model no.					
Pilot	1	2	3	4	5	6
A	3.5	4.0	4.0	5.0	5.5	3.5
	3.0	4.0	3.5	4.5	6.5	4.0
B	3.0	2.0	4.0	4.5	4.5	4.5
	3.0	4.0	4.0	5.0		6.0
C	2.0	5.0	4.0	7.0	7.0	6.5
	3.0	3.0	3.0		6.5	
D	6.0	3.0	3.0	4.0	4.5	6.0
E	3.0	3.0	5.0	5.0	6.0	7.0
F	2.5	3.0	3.0	5.0	4.0	4.5
G	2.5	4.0	4.5	4.5	4.0	6.0
Mean	3.15	3.50	3.80	4.94	5.40	5.33
Standard deviation	1.06	0.88	0.54	0.845	1.12	1.22

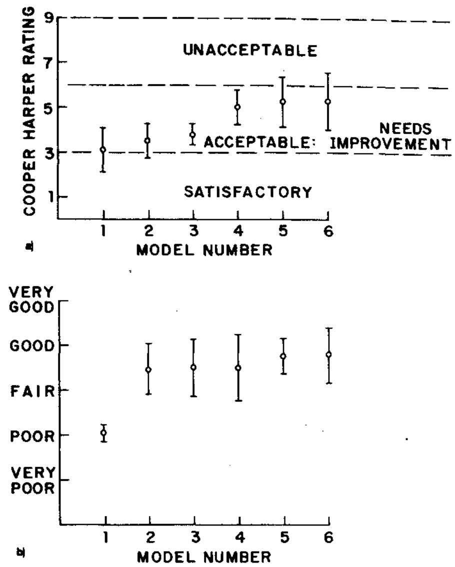

Fig. 4 a) Handling-quality ratings. b) Realism of turbulence.

been statistically analyzed for many of the properties of turbulence, only two of which are discussed here.

Here we will focus our attention on the pilot handling-quality ratings and the realism of the turbulence. The Cooper-Harper Ratings of each of the test runs, and for each pilot, have been tabulated in Table 4. The pilot opinion ratings show a definite trend. The ratings progressively increased (worse handling quality) as the pilots encountered more composite and sophisticated turbulence models. When using the Gaussian Model, the simplest of all the models, the handling quality was rated in the satisfactory range by almost all the pilots. On the other hand, for approximately the same level of rms intensity, the pilot opinion of handling quality was considerably worse for the Modified Gaussian, Rayleigh, and the UVA Turbulence Models. Figure 4a shows the mean Cooper-Harper ratings for each of the six turbulence cases. It may be observed that at approximately the same rms intensities of turbulence, the handling-quality ratings transit from the satisfactory level, for the simple Gaussian Model, to an unacceptable level for the more compositely structured UVA Turbulence Model. Although the mean for the worst-case does not reach the unacceptable level, one standard deviation about the mean does. This implies a nonnegligible fraction of the pilots rate the handling unacceptable. Figure 4b presents the pilot opinion of the realism of turbulence. The correlation coefficient between the handling-quality ratings and the realism of turbulence is 0.74. This high correlation indicates that the handling-quality ratings are considerably worse for the more realistic turbulence models. The UVA turbulence model, which most closely matches the properties of real atmospheric turbulence, of all the models tested here, is rated worse on the Cooper-Harper Scale than the less realistic Gaussian Turbulence model for approximately the same level of turbulence intensity.

Conclusions

From the flight test results of this program, it is apparent that the pilot's ability to handle the airplane in a turbulent environment not only depends on the rms intensity, but also the composition and the structure of turbulence.

Pilots rated handling qualities in the satisfactory range while flying in a turbulence environment simulated by a simple Gaussian Model; whereas the handling-quality ratings degraded while flying in a turbulence environment simulated by the UVA Turbulence Model of approximately the same intensity. In fact, the handling-quality ratings monotonically degraded as the pilots encountered more complex and realistic turbulence models. It may, therefore, be concluded that handling-quality studies, using motion-based simulators, are critically affected by the suitable choice of realistic turbulence model in addition to the appropriate rms intensities of turbulence.

These tests were conducted in a simulated environment of a light general aviation STOL airplane. Caution should be exercised, therefore, in applying and extending the results to a general aircraft configuration.

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