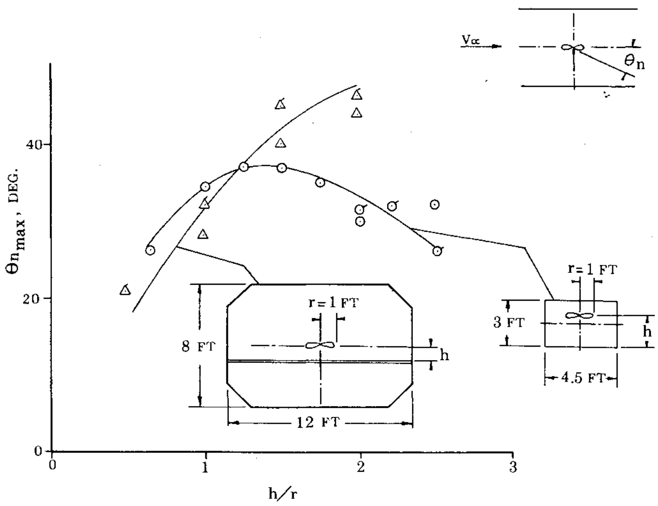

Fig. 2 Allowable wake deflection angle for vertically off-centered rotor.

by the h/r ratio. This is evidenced by the agreement of the two curves in the figure for $h/r<1.25$ to $h/r>1.25$; the small test section (3×4.5 ft) shows a decrease in the allowable $\theta_{n_{max}}$ which is believed to be caused by the impaired inflow to the rotor due to the close presence of the ceiling. On the other hand, $\theta_{n_{max}}$ for $h/r>1.25$ in the large test section (8×12 ft) with ground plane does not exhibit such a decrease, which is understandable because its ceiling height is large (four times the rotor radius), thus causing no significant effect on the lift of the rotor.

IV. Conclusions

There are two conclusions that can be drawn from the present data:

1) For rotors tested with a ground plane or in the vicinity of the floor, the h/r ratio defines the low-speed test limits.

2) For rotors tested vertically off-centered in a test section, the ultimate location is the centerline to obtain the lowest allowable minimum speed test limit. Rotors located either below or above the vertical centerline will suffer a loss of the allowable low-speed test limit at the approximate rate of the net momentum angle of 20 deg per h/r ratio.

Acknowledgment

This work was sponsored by the U.S. Army Research Office, Durham, N. C., under Grant DA-ARO-D-31-124-G1144, and NASA Grant No. NGR-48-002-035.

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Handling Qualities of Aircraft in the Presence of Simulated Turbulence

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Introduction

In an earlier paper,[1] the authors have shown that Instrument Flight Rule (IFR) handling-quality studies, in the presence of simulated turbulence, are critically affected by the suitable choice of a realistic turbulence model. The purpose of this Note is to present additional results obtained from flight simulator experiments on Visual Flight Rule (VFR) approach landings of a STOL type aircraft.

Reference 1 describes the four basic turbulence models tested on the NASA Langley Research Center Visual Motion Simulator (VMS): model 1 – Gaussian, models 2 and 3 – Modified Gaussian, model 4 – Rayleigh, and models 5 and 6 – Variable Length and Intensity (VLI). The details of the turbulence field generated by each of these models is presented in Ref. 2, where they are compared with measured real atmospheric turbulence.

Each of the turbulence models was simulated on the VMS with a pilot in the control loop. The flight simulator experiment was conducted for two sets of landing conditions. The first required the pilot to follow an IFR tracking task with no visual cues provided. The results of this study were discussed in Ref. 1. For the second condition, the simulator was equipped with a visual display that provides a realistic landing approach scene. Pilot opinion ratings (of the landing approach with visual display) were analyzed to establish the most realistic turbulence model and to identify the variables that critically affect the handling quality of aircraft in turbulence.

Aircraft Simulator

The Visual Motion Simulator (VMS) at the NASA-Langley Research Center, a synergistic motion base simulator with the basic interior and instrumentation of a jet transport cockpit, was employed to simulate the Canadian deHavilland DHC-6 Twin Otter. The simulator is equipped to provide two sets of conditions. In the first set of conditions the pilot flies straight and level and is not given any visual or "out the window" cue. In the second set, the pilot flies a landing approach and is given a visual display that generates a realistic landing scene. The aircraft motion signals, through a feedback loop, run a video camera on a scale model of the airfield and its

Received Nov. 14, 1977; revision received Dec. 9, 1977.

Index categories: Handling Qualities, Stability and Control; Simulation.

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surroundings. In addition, the simulator is equipped with Instrument Landing System (ILS) instrumentation, which includes both a flight director and a raw display. Both 20- and 30-deg flaps are provided for the landing approach.

Pilot Task Performance

In the landing approach test program, eleven pilots (experienced in civil, military, and research flying) "flew" the VMS. Three of the eleven pilots had over 2000 hours in the Twin Otter. Test runs, each of 6-8 minutes duration for each of the turbulence models, were made in a pilot session. During separate sessions, all the pilots repeated the six models in a random order. The pilots flew a constant altitude tracking task until the glide slope was intercepted. The pilots were then required to approach on a 6-deg glide slope using both the ILS and the visual display. The simulation is terminated at touchdown. After each run the pilot, through a questionnaire, was asked to estimate the turbulence intensity, realism, relative amplitude of aircraft motions in each of the three degrees of freedom, patchiness, and workload, and to give a Cooper-Harper[3] handling quality rating for the airplane/turbulence interaction. Additional questions explored the bases for the pilots judgements. In addition, the pilots were also asked to estimate the altitude, terrain, and atmospheric stability in relation to their flying experience.

Continuous strip-chart recordings were made displaying time histories of various aircraft parameters for later analysis.

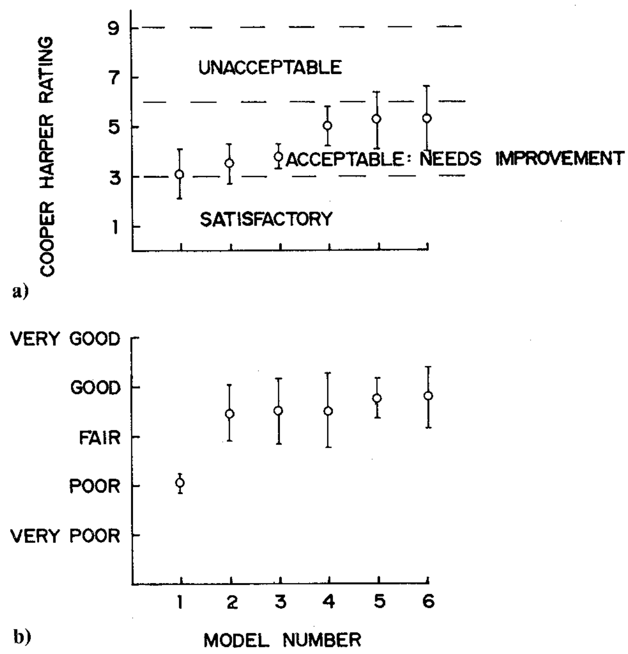

Fig. 1 a) Handling quality ratings (without visual aid). b) Realism of turbulence (without visual aids).

Results and Discussion of Simulation

Figures 1 and 2 present pilot opinion ratings of handling quality and the realism of turbulence both with and without the visual cue. The handling quality ratings transit from the satisfactory level, for a simple Gaussian model, to an unacceptable level for the more realistic and compositely structured VLI turbulence model (models 5 and 6). By comparing Figs. 1 and 2, it may be observed that the visual display did not alter this trend.

The Gaussian model (model 1) was found to be too continuous by almost all the pilots both with and without the visual display. On the other hand, the Rayleigh model (model 4) was rated about right as was the VLI model.

Frequency content ratings for the Gaussian model were poor, whereas the mean ratings of the Rayleigh (model 4) and VLI (models 5 and 6) turbulence models were "about right."

In the visual landing approach, pilot task performance was measured by how well a pilot performed in tracking the ILS. Here it was observed that the pilots had greater difficulty in tracking the ILS for the compositely structured VLI model than the simple Gaussian model.

Tables 1 and 2 present the correlation matrix for various turbulence properties and aircraft handling qualities. Several important observations can be made from these matrices. From Table 1 (level flight), the realism of turbulence is highly correlated with patchiness (0.58), element of surprise (0.63), and frequency content (0.52). This shows that in the opinion of pilots, the realism of a turbulence model is closely linked to the physical properties of the real atmosphere. In addition, the high correlation between handling qualities and realism (0.74) indicates that the handling qualities are considerably worse for more realistic turbulence models. The low correlation between the patchiness characteristics and the intensity of turbulence (0.07) shows that the non-Gaussian patchiness characteristics cannot be induced by simply chosing a higher level of intensity (rms). On the other hand, patchiness is correlated to frequency content (0.45) and handling quality. Table 2 shows the same trend. Here pilot

Table 1 Correlation matrix (without visual cue)

	Turbulence intensity	Realism	Patchiness	Frequency content	Element of surprise	Handling quality
Turbulence intensity	1.0	0.36	0.07	−0.16	0.54	0.27
Realism	0.36	1.0	0.58	0.52	−0.63	0.74
Patchiness	0.07	0.58	1.0	0.45	0.39	0.50
Frequency content	−0.16	0.52	0.45	1.0	0.23	0.63
Element of surprise	0.54	−0.63	0.39	0.23	1.0	−0.02
Handling quality	0.27	0.74	0.50	0.63	−0.02	1.0

Table 2 Correlation matrix (with visual cue)

	Turbulence intensity	Realism	Patchiness	Frequency content	Element of surprise	Handling quality	Pilot error
Turbulence intensity	1.0	0.41	0.21	0.18	0.27	0.31	0.43
Realism	0.41	1.0	0.60	0.49	0.36	0.70	0.38
Patchiness	0.21	0.60	1.0	0.46	0.38	0.47	0.54
Frequency content	0.18	0.49	0.46	1.0	0.31	0.66	0.11
Element of surprise	0.27	0.36	0.38	0.31	1.0	0.31	0.16
Handling quality	0.31	0.70	0.47	0.66	0.31	1.0	0.68
Pilot error	0.43	0.38	0.54	0.11	0.16	0.68	1.0

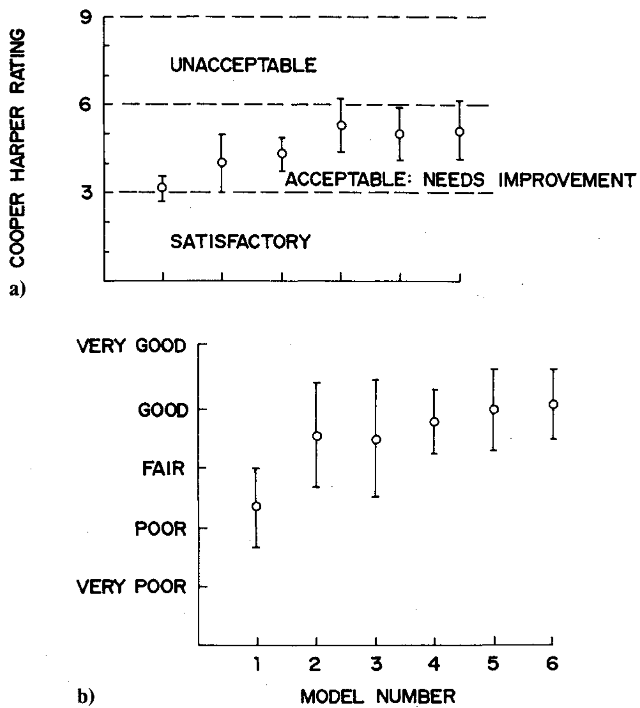

Fig. 2 a) Handling quality (ILS, with visual aid). b) Realism of turbulence (ILS, with visual aid).

error is highly correlated with handling quality and patchiness.

Conclusions

From the analytical and experimental study of the time histories generated by the six turbulence models, the following conclusions can be drawn:

1) Of all the gust models tested, turbulence simulated by the VLI models adequately match the desired statistical properties of real atmospheric turbulence.

2) Aircraft handling quality and pilot task performance are critically affected by turbulence. Realistic turbulence models present greater difficulty in controlling the aircraft than simple Gaussian models.

3) The correlation (0.54) between task performance and patchiness suggests that the patchiness of the simulated turbulence plays an important role in the pilot's ability to handle an aircraft.

4) The high correlation coefficient between handling quality and realism (0.74 and 0.70) indicates that the handling qualities are considerably worse for more realistic turbulence models in both IFR and VFR piloting tasks.

5) It is apparent that a pilot's ability to handle an airplane in a turbulent environment not only depends on the rms intensity, but also the composition and structure of turbulence. Pilots rated handling in the satisfactory range while flying in a turbulence environment simulated by a simple Gaussian model; however, the handling quality ratings degraded while flying in a turbulence environment simulated by the VLI turbulence model of approximately the same intensity. In fact, the handling quality ratings monotonically degrade as the pilots encountered more complex and realistic turbulence models. It may be concluded, therefore, that handling quality studies, using motion-base simulators, are critically affected by the suitable choice of a realistic turbulence model in addition to the appropriate rms intensities of turbulence.

Acknowledgment

This work has been sponsored by NASA under Grant NGR 47-005-208.

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