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Powered-Lift Aircraft Handling Qualities in the Presence of Atmospheric Disturbances

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Selected results are presented from a two-phased experimental program to investigate powered-lift aircraft handling quality degradation due to both naturally-occurring and computer-generated atmospheric turbulence. In phase I a variable stability helicopter was flown to simulate a powered-lift aircraft on final approach. In phase II a ground-based simulator with a moving cockpit and a colored visual display was used to represent the same powered-lift aircraft. During phase II a Dryden model of atmospheric turbulence was used together with actual wind profiles recorded during phase I. This paper focuses on the phase II results, which demonstrate that the Dryden model can yield optimistic ratings of airplane handling qualities in turbulent landing conditions. The model also leads to an optimistic estimate of combined pilot-vehicle performance degradation in turbulent flight.

Nomenclature

AGL = above ground level
CH = Cooper-Harper rating
IFR = instrument flight rules
L_u = longitudinal gust scale length
s = Laplace operator
V = airspeed
VFR = visual flight rules
Z_u = aircraft stability derivative for vertical force with respect to airspeed
ζ_h = effective damping ratio of pilot-vehicle combination with altitude regulation
θ = pitch attitude
σ_h = rms deviation of altitude about the mean value
σ_{u_a} = rms deviation of airspeed about the mean value
σ_{u_g} = rms deviation of longitudinal gust component of turbulence about the mean value
ω_h = effective bandwidth (undamped natural frequency) of pilot-vehicle combination with altitude regulation
ω_u = effective bandwidth of pilot-vehicle combination with airspeed regulation

Introduction

A PROGRAM to investigate powered-lift aircraft handling quality degradation due to naturally-occurring and computer-generated atmospheric turbulence was conducted by the National Aeronautical Establishment (NAE) of the National Research Council (NRC) of Canada and the Federal Aviation Administration (FAA) of the United States Department of Transportation. The primary objectives of this program were two-fold:

1) To investigate the handling quality degradation of powered-lift aircraft in flight while performing the final approach and landing flare in the presence of significant atmospheric disturbances, and

2) To determine the degree to which this flight experiment could be transferred to and its results duplicated on a modern ground-based simulator with six-degrees-of-freedom in motion and a colored visual display.

Various atmospheric turbulence models have been proposed for use in airworthiness certification testing by means of ground-based flight simulation. Some of these turbulence models were also employed in the ground-based portion of this experimental program. Two secondary objectives, therefore, were:

1) To qualify the conditions under which some of the atmospheric turbulence models provide reasonable representations of naturally-occurring turbulence, and

2) To help to define a low altitude turbulence model for use in airworthiness certification testing.

The experimental investigation was conducted in two phases. The first phase (phase I) involved flight tests conducted by the NAE using a variable stability helicopter[1] to simulate a representative powered-lift aircraft in the approach and landing configuration. The second phase (phase II) involved ground-based simulation tests conducted by the FAA on the Flight Simulator for Advanced Aircraft[2] (FSAA) at the NASA Ames Research Center, Moffett Field, California. Systems Technology, Inc. (STI) was responsible for the design and implementation of the ground-based simulator model[3] and the analysis of the phase II data. This paper focuses on the results of the phase II experiments. Some of the phase I results were documented by Sinclair et al.[4] A comparison of results from phases I and II will be made in a forthcoming report.[5]

Technical Approach

The phase II experiments were divided into two separate tasks. Task I used primarily the wind profiles of naturally-occurring atmospheric turbulence. These wind profiles were

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recorded during the phase I experiments in the spring and winter of 1976. The 75 wind profiles recorded included runs with rms turbulence levels ranging from 1.0 to 6.0 ft/s. The runs recorded during the winter in Ottawa included wind shears that ranged from a 60 ft/s tail wind aloft to a 20 ft/s head wind on the ground. Task II used the Dryden model of computer-generated atmospheric turbulence.[6] The rms turbulence level was varied between 1.5 and 6.5 ft/s. No attempt was made to model wind shears independently, but the Dryden turbulence was superimposed on steady head winds and cross winds.

The scenario for both tasks I and II was to capture a 6-deg glide slope at approximately 1800 ft AGL, to perform an IFR approach at 65 knots down to 200 ft AGL, and to complete the approach under visual conditions. The pilots were instructed to perform the flare but not to touch down. For each run the pilots completed an evaluation questionnaire, and a digital computer calculated a variety of performance parameters.

The task I evaluation questionnaire requested the pilot to:

1) Describe the effect of atmospheric disturbances on task performance,
2) Estimate the magnitude of his tracking errors,
3) Give Cooper-Harper handling quality ratings for the IFR and VFR-flare segments of each approach under the prevailing conditions, and
4) Comment on the most difficult feature of the approach.

The task II evaluation questionnaire has been used in other investigations of computer-generated turbulence models.[7,8] The task II questionnaire requested the pilot to:

1) Rate the intensity, realism, frequency content, and patchiness of the turbulence,
2) Estimate his workload and task performance, and
3) Give a Cooper-Harper rating of the handling qualities of the aircraft under the prevailing conditions.

The four pilots who participated in the NAE airborne experiments also participated in the FAA ground-based simulation. All of the subject pilots were highly experienced with both fixed-wing and rotary-wing aircraft, as well as with ground-based simulators. During the task I experiments each pilot flew the same runs in the ground-based simulator as he did in the airborne simulator. In addition, all of the pilots were exposed to selected wind profiles that contained large wind shears and/or high rms turbulence levels.

Results

Selected results from tasks I and II are presented below. For brevity, the data for only one of the subject pilots is presented; however, the trends are representative of those collected for all of the subject pilots.

Figure 1 shows the Cooper-Harper ratings for the IFR segment vs the longitudinal rms turbulence level, σ_{u_g}, for one of the subject pilots. The task I and task II data are indicated by circles and squares, respectively, with the solid data points representing task I runs having "significant wind shears." The linear regression lines and correlation coefficients (r) shown were computed 1) with all of the task I data (– – – –) for one of the pilots, 2) with the significant wind shear cases removed from his task I data (———), and 3) with all of his task II data (– · –). The correlation coefficient is a measure of the goodness of the fit achieved by the linear regression. Values of r close to unity indicate less variability in the data than values close to zero.

One can see from Fig. 1 that the correlation coefficient increases when data from runs with significant shears are deleted, although the regression line does not change dramatically. This implies that wind shear may be responsible for some of the variability in the data. Note that the variability in the task II results is much less than the variability in the task I results, even when the significant wind

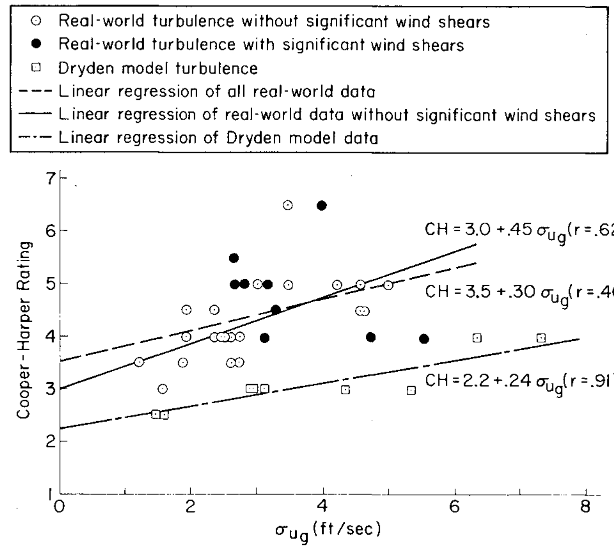

Fig. 1 IFR Cooper-Harper rating vs longitudinal rms turbulence level (Pilot C).

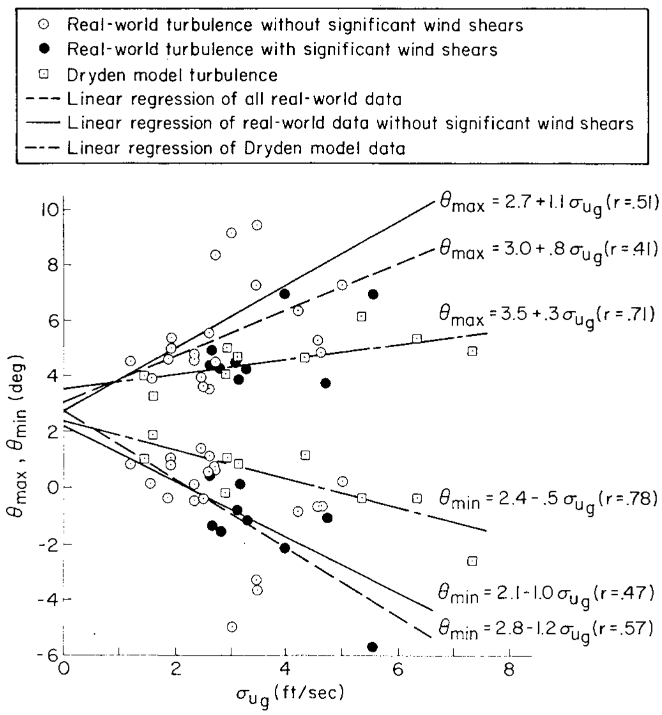

Fig. 2 IFR pitch attitude extrema vs longitudinal rms turbulence level.

shear cases from the task I data are removed. An hypothesis for this higher variability will be presented shortly.

In addition, the ordinate intercepts shown in Fig. 1, which reflect the Cooper-Harper rating for calm air, are numerically higher in the task I results. Thus it appears that the handling qualities obtained with the real-world wind profiles are inferior to those obtained with the Dryden model of computer-generated turbulence.

Some typical pilot-vehicle performance data for one of the subject pilots are depicted by the linear regression curves and correlation coefficients shown in Figs. 2 and 3 which present pitch attitude extrema and airspeed extrema, respectively, vs σ_{u_g}. Comparing the task I and task II data, one can see that the task I pitch attitude and airspeed variability is greater than in task II, even when the significant wind shear cases are removed from the task I data. This indicates that, like han-

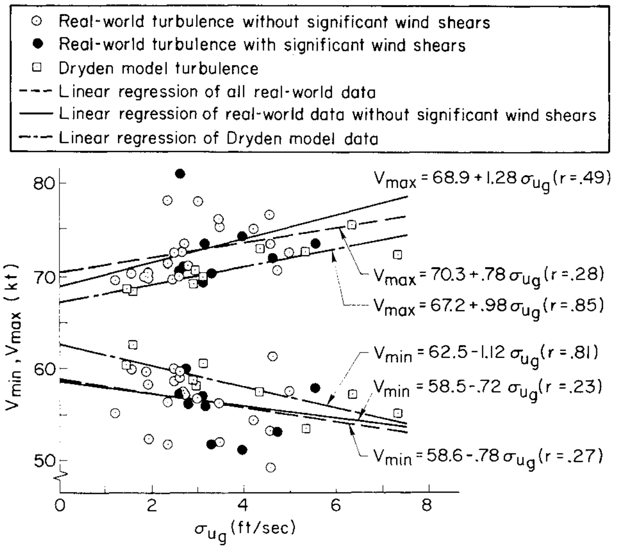

Fig. 3 IFR airspeed extrema vs longitudinal rms turbulence level.

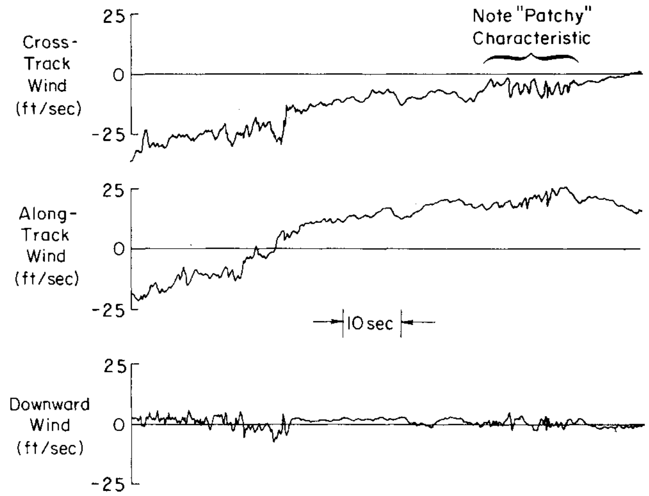

Fig. 4 Real-world wind profile demonstrating patchy characteristics of turbulence.

dling qualities, the pitch attitude and airspeed regulation performance obtained with naturally-occurring turbulence is inferior to the performance obtained with the Dryden model of turbulence.

Similar results were reported by Jacobson and Joshi.[8,9] They reported that different handling qualities were obtained from non-Gaussian models of computer-generated atmospheric turbulence, as compared with ratings from a Gaussian model. The rms turbulence level for all the models was about the same.

Partially conflicting results were reported by P.M. Reeves et al.[7] Reeves compared handling qualities and pilot-vehicle performance obtained from one real-world time history of turbulence, one Gaussian model, and two non-Gaussian models of computer-generated turbulence. (The rms levels of the computer-generated turbulence were all scaled to be the same as the real-world rms turbulence velocity.) He reported that the handling qualities ratings were not affected by the different turbulence sources, but that pilot-vehicle performance was poorest for the real-world turbulence. Pilot-vehicle performance for all the computer-generated turbulence models was similar.

Returning to the issue of the variability in the data, note that the correlation coefficients shown in Figs. 2 and 3 generally increase when the significant wind shear cases from the task I data are removed. This suggests that some of the variability in the data is due to the wind shears, but there are other instances where the correlation coefficients are either unchanged or actually reduced after the significant shear cases are removed. Thus we must infer that there are properties other than wind shear responsible for some of the variability in the data. We shall now present an hypothesis for the observed variability.

Discussion and Conjecture

The most likely other property responsible for the observed variability is the so-called patchy characteristic of the turbulence. This characteritic is demonstrated in the wind profile shown in Fig. 4. Regions of relatively high frequency, larger amplitude disturbances are both preceded and followed by lower amplitude, and possibly lower frequency, disturbances. Because of the patchy regions in the wind profile, the rms turbulence level measured over the entire run is not a very representative measure of the actual atmospheric disturbances. A more meaningful metric would be, for example, the distribution (or histogram) of rms levels measured over shorter time intervals. Reference 10 demonstrates how the rms turbulence level of the Dryden model and a non-Gaussian model of turbulence[11] vary when measured over shorter time intervals. The choice of the length of such intervals should be based on the known characteristics of the closed-loop pilot-vehicle system. If the bandwidth of the outer-loop control variables such as airspeed and path deviation were in the neighborhood of 0.05 to 0.20 rad/s, then the time intervals of interest to the pilot should be in the range from 5 to 20 s.

It is believed that a more satisfactory representation of atmospheric turbulence might be provided by the Dryden model with a time-varying rms level exhibiting the correlated pulse-like character among the three components shown in Fig. 4. The atmospheric turbulence model documented in Ref. 12 uses a scheme similar to this. However, the validity of this model and, indeed, of the many new turbulence models currently available, needs to be demonstrated through piloted flight simulation.

Patchiness imposes an element of surprise in the pilot's regulation against disturbances and forces the pilot to modify his control strategy in order to maintain the same overall performance. This unexpected readaptation of control strategy is viewed as additional workload which leads to inferior pilot rating.

To demonstrate how the pilot maintains the same overall performance, consider the following approximate transfer function for the closed-loop height deviation response to longitudinal gust:

$$\frac{h}{u_g} \doteq \frac{Z_u}{s^2 + 2\zeta_h \omega_h s + \omega_h^2} \tag{1}$$

where ζ_h and ω_h are the effective closed-loop damping ratio and undamped natural frequency, respectively. If we use the Dryden spectral function for u_g, then it can be shown[13] that the height-to-longitudinal gust velocity variance ratio is approximately

$$\frac{\sigma_h^2}{\sigma_{u_g}{}^2} = \frac{Z_u^2\left(1 + \dfrac{2\zeta_h\omega_h}{V/L_u}\right)}{2\zeta_h\omega_h^3\left(2\zeta_h\omega_h + \dfrac{\omega_h^2}{V/L_u} + V/L_u\right)} \tag{2}$$

where V is the airspeed and L_u is the scale length. The ratio V/L_u, the break frequency of the first order Dryden shaping filter, reflects the bandwidth of the disturbance.

Figure 5 is a plot of the ratio σ_h/σ_{u_g} vs V/L_u for the test aircraft's value of Z_u, one value of ζ_h, and two values of ω_h. For the aircraft which we investigated, the pilot can increase

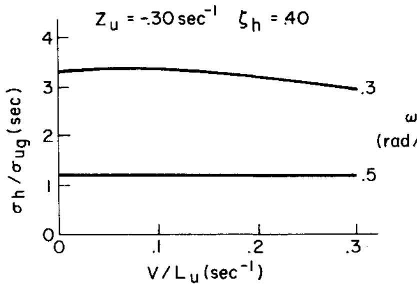

Fig. 5 rms flight path deviation as a function of rms longitudinal gust, bandwidth of the gust, and bandwidth of the flight path loop.

ω_h by increasing the gain of his throttle displacement response to his perceived height deviation. The indicated values of ω_h would correspond to moderate and tight throttle-to-height loop closures. The effective damping ratio ζ_h was held constant because the pilot would close a tighter loop only if he could maintain an adequate phase margin.

Figure 5 shows that σ_h/σ_{u_g} does not change much with the bandwidth of the gust V/L_u^g but changes more dramatically with the bandwidth of the flight path loop ω_h. Thus if the pilot does not immediately increase ω_h when flying through a patchy region of turbulence, the performance as reflected by σ_h will suffer.

An expression similar to Eq. 2 can be derived for the rms airspeed deviation.[13] The result is

$$\frac{\sigma_{u_a}^2}{\sigma_{u_g}^2} = \frac{V/L_u}{V/L_u + \omega_u} \tag{3}$$

where ω_u is the effective bandwidth of the speed loop. This indicates that if σ_{u_g} is increased the pilot must also increase ω_u in order to maintain the same value of σ_{u_a}. For the aircraft which we investigated, the pilot can increase ω_u by increasing the gain of his pitch attitude control response to his perceived airspeed deviation.

Just how ω_u and ω_h do, in fact, change with respect to the pilot's judgement of σ_u and σ_h are matters which require further investigation. The result would be a better understanding of the relationships among pilot-vehicle performance, disturbance levels, and pilot opinion.

During the task II portion of the experiment the pilots were asked to rate the realism and patchy characteristics of the turbulence. The pilots were told that "patchiness" refers to variations in the intensity of the turbulence. The histogram of Fig. 6 summarizes the data collected for all subject pilots. The results indicate that virtually all runs in which the turbulence realism was rated "good or very good" are runs in which the patchiness of the turbulence was judged "about right," that is, not too continuous or too patchy. Runs in which the turbulence realism was rated "fair or poor" were nearly always runs in which the continuity of the turbulence was judged to be unrealistic. Thus it appears that proper variation in the turbulence intensity is very important to the pilots' perception of realism of the turbulence.

Conclusions and Recommendations

Simulator use of the Dryden model of computer-generated turbulence yields better handling quality ratings and pilot-vehicle performance than can be obtained in significant levels of naturally-occurring atmospheric turbulence, even when the effects of wind shear are accounted for and both sources of turbulence have comparable root-mean-square velocity. Also, the variability in the handling quality ratings and pilot-vehicle performance data obtained with the Dryden model is lower than that for similar data obtained with naturally-occurring atmospheric turbulence, even when the effects of wind shear are accounted for. Although some of the variability in the

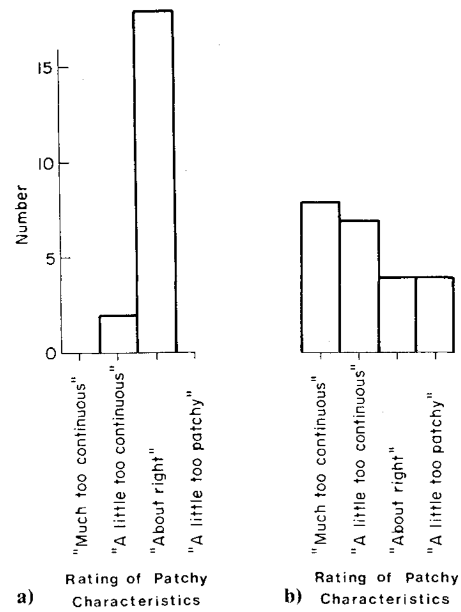

Fig. 6 Histograms of patchy characteristic ratings for a) good or very good and b) fair or poor turbulence realism ratings for all task II data.

data is due to the wind shears, there are instances where the variability in either the handling quality or pilot-vehicle performance data with naturally-occurring disturbances is either unchanged or increased after the effects of wind shear are accounted for.

The reason for the preceding discrepancies is believed to be the patchy characteristic of the naturally-occurring atmospheric turbulence. In this respect, the rms turbulence level measured over the entire run is not a necessarily representative measure of the actual atmospheric disturbance. A more meaningful metric would involve the distribution of rms turbulence levels measured over shorter time intervals in the range from 5 to 20 s.

The patchy regions in the turbulence impose an element of surprise in the pilot's disturbance regulation task. As a consequence, the pilot must modify his control strategy in order to maintain the same overall performance. This unexpected readaptation of control strategy is viewed as additional workload which leads to inferior pilot rating.

Finally, the patchy characteristic of the atmospheric disturbance appears to be important to the pilot's perception of the realism of the turbulence. This is based on the correlation of subjective ratings by the pilots with the subjective judgment of realism and patchy characteristic of the disturbances encountered. We therefore recommend that patchiness be incorporated into computer-generated turbulence models.

There are a number of researchers currently investigating novel atmospheric turbulence models (Refs. 14-17), and we can therefore expect to see some improvements in both the fidelity and diversity of computer-generated atmospheric turbulence models in the near future.

Acknowledgment

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