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Non-Gaussian Atmospheric Turbulence Model for Flight Simulator Research

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The present turbulence model is the result of a continuing effort in improving the realism of the NLR flight simulator. The turbulence simulation has evolved from a simple three-component Gaussian model to a complex five-component model. It has the following characteristics of naturally occurring turbulence: intermittency, patchiness, influences of altitude and windspeed on scale length and intensity, and "above/below clouds" effect. Handling qualities ratings and pilot-aircraft performance were evaluated for a range of turbulence settings concerning intermittency and patchiness. Based on the results of the present simulation study, a turbulence model with realistic characteristics including combined effects of intermittency and patchiness is recommended for application in handling quality simulation investigations.

Nomenclature

F = "global intermittency" parameter $= 0 \leq F < 1.0$
h = height above ground level
H = filter transfer function
$i(t)$ = intermittent signal
L_g = turbulence scale length
L_p = average patch length
L_s = ramp length of high-frequency constituent $= L_g/32$
$p(x)$ = probability density distribution function
Q = patchiness intensity factor
R = patch length factor $= L_g/L_p$
s = Laplace operator
u_g, v_g, w_g = symmetrically distributed turbulence velocities
$\hat{u}_{g_a}$ = u_{g_a}/V_a = nondimensional asymmetrically distributed u_{g_a}
V_a = airspeed
V_w = windspeed
α_{g_a} = w_{g_a}/V_a = nondimensional asymmetrically distributed w_{g_a}
σ = standard deviation
τ = filter time constant

Indices

u = longitudinal turbulence
v = lateral turbulence
w = vertical turbulence

Introduction

RECENT studies[2,3] have shown that in simulator investigations the turbulence model can have a major effect on handling quality ratings and pilot-aircraft performance. The turbulence simulation should be as realistic as possible to enable an extrapolation to the real atmosphere.

The basis for the NLR turbulence simulation is a model generating intermittent turbulence velocities as developed by Tomlinson[4] of RAE-Bedford. Recently the NLR turbulence model as used on the moving base research simulator was improved, and now has the possibility to generate intermittency and patchiness which are separately controllable.

Patchiness is the alternation of periods of low and high intensity, whereas intermittency is the property of pronounced changes in the turbulence velocities within a patch. This paper presents the results of an evaluation program that was conducted to determine the influence of model parameter settings on realism and handling quality ratings.

General Characteristics

The NLR turbulence model generates three symmetrically distributed components (u_g, v_g, and w_g), and two asymmetrically distributed components ($\hat{u}_{g_a}$ and α_{g_a}). $\hat{u}_{g_a}$ and α_{g_a} account for the spanwise variation of the turbulence field and produce roll and yaw moments.

The intensity of the turbulence velocities is proportional to the windspeed V_w. For neutral atmospheric conditions this factor is chosen equal to 0.1.

$$\sigma_{u_g}, \sigma_{v_g}, \sigma_{w_g} = 0.1 V_w$$

The rms of the vertical turbulence velocity w_g and the asymmetrically distributed α_{g_a} is decreased below a height of 90 m according to Table 1. The intensity of u_g, v_g, and $\hat{u}_{g_a}$ is independent of height.

To simulate the effect of flying above/below clouds, all turbulence velocities are proportional to a "cloud factor." This factor is 0.1 at cloud-top height and increases to 1.0 at

Table 1
rms of w_g and α_{g_a} vs height[a]

Height, m	rms, %
90	100
42	80
11	50
5	0

[a] Adapted from MIL-F-8785.

Table 2
Turbulence scale lengths[a]

Height, m	$L_{u,v}$, m	L_w, m
750	480	480
240	480	152
90	480	52
48	320	29
5	160	18

[a] Adapted from MIL-F-8785.

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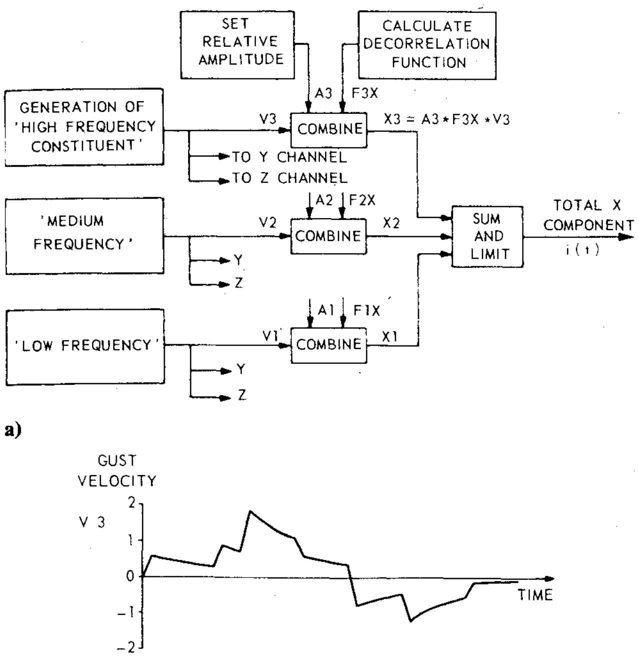

Fig. 1 a) Overall system (X channel); b) "High" frequency, raw constituent, $F = 0.8$.

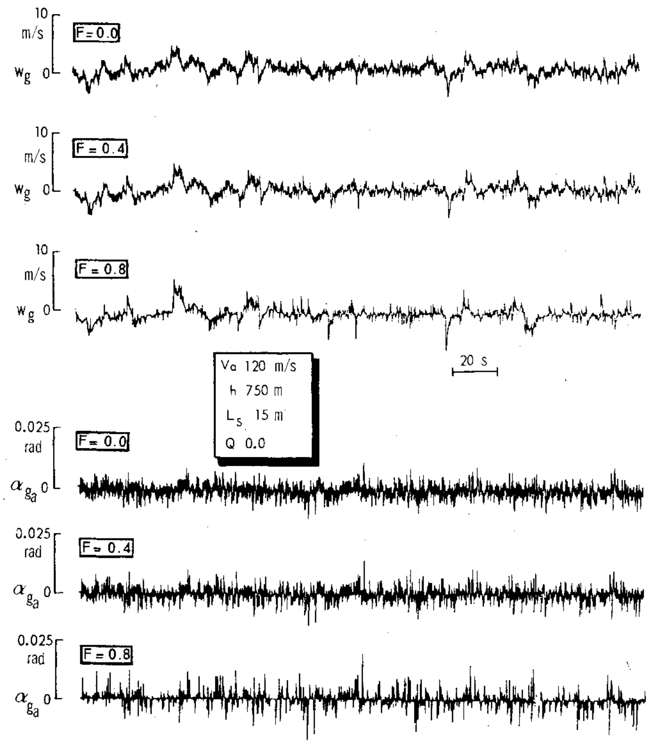

Fig. 2 Typical time histories of turbulence signals for several values of the "global intermittency" parameter F.

cloud-base and below. Especially during an approach the cloud factor gives the impression of flying from a calm blue sky into the clouds with associated turbulence.

The power spectral density functions of u_g, v_g, and w_g show the $-5/3$ slope of real turbulence. The scale lengths for this model are a function of height as shown in Table 2.

Patchiness and Intermittency[5]

Turbulence velocities as encountered in real flight show an essentially non-Gaussian behavior, that can be described as patchiness and intermittency. Patchiness is the relatively low-frequency variation of the turbulence intensity, resulting in patches with high and low activity. Intermittency is observed as more pronounced changes in turbulence velocities as compared with Gaussian signals.

These two properties can be distinguished by considering the probability density distributions of the turbulence velocity and its derivative. Both distributions will show deviations from the Gaussian. In the case of intermittency the derivative distribution is affected more than the velocity distribution, whereas for patchiness the contrary applies to a lesser extent. A useful description of a non-Gaussian distribution is the fourth-order central moment or kurtosis. For a Gaussian distribution this takes the value 3, while for real turbulence values up to about 6 are found. The kurtosis of the velocity derivative has a higher value than the kurtosis of the velocity itself, indicating the intermittent behavior of the turbulence.

Short Description of the Intermittent Turbulence Model (RAE-Bedford)[4]

A general block diagram of the overall process is illustrated in Fig. 1a. Three independent time-sequences of velocity fluctuation are generated, with each sequence having a different characteristic gust gradient and thus containing power at different dominant frequencies, loosely termed "high," "medium," and "low." Three sequences were considered to provide sufficient coverage of the frequency range of interest to manual flight. Each sequence feeds all three aircraft axes (x,y,z). To remove the perfect correlation that exists at this stage, a decorrelation procedure is applied, involving random switching. Within each channel, the relative amplitudes of each constituent are adjusted to give a power spectrum curve

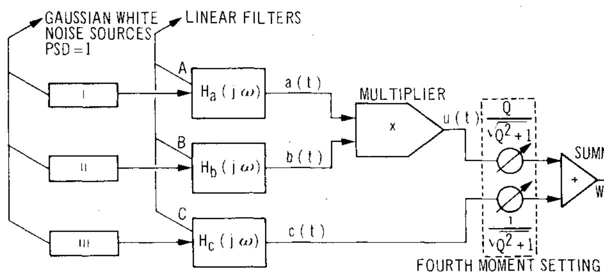

Fig. 3 Block diagram, representing the generation of a non-Gaussian process having an arbitrary fourth-order moment: $3\sigma^4 < m_4 < 9\sigma^4$.[6]

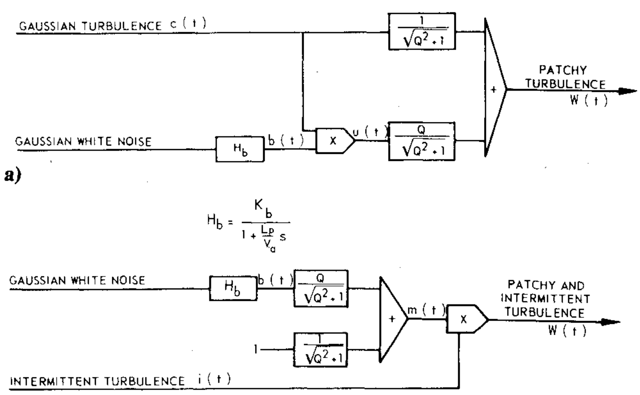

Fig. 4 a) Alternative generation of patchiness; b) block diagram, representing the generation of patchy and intermittent turbulence.

with the desired slope at high frequencies (viz., A1, A2, A3 in the figure) and the three constituents summed to give the total component in one axis. A final, overall scale factor is applied externally to give a selected root-mean-square intensity.

On a proportion of occasions, controlled by the single parameter F, the amplitude distribution returns a zero gust

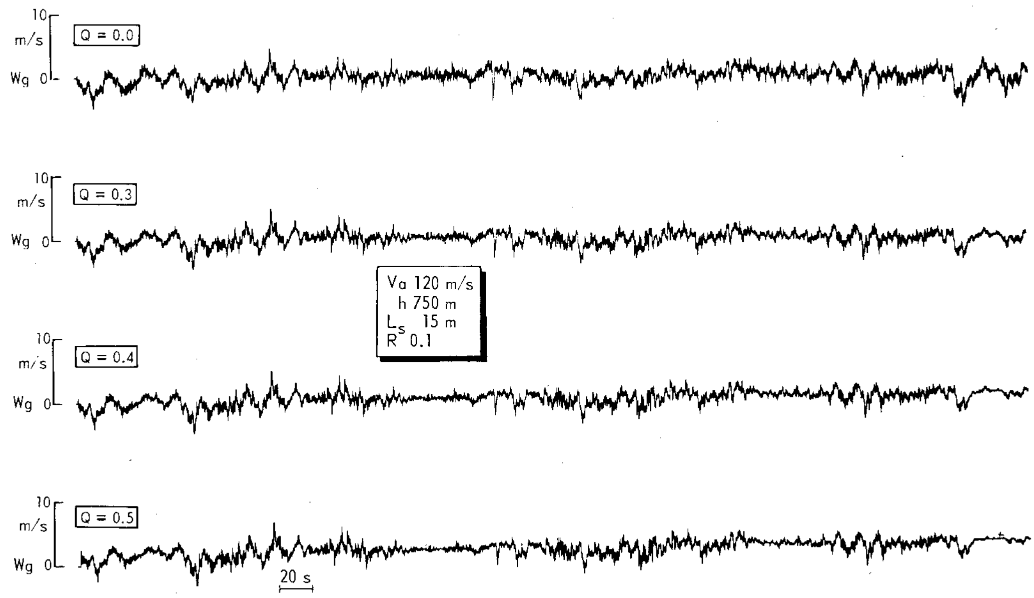

Fig. 5 Typical time histories of turbulence signals for several values of the "patchiness intensity" parameter Q.

and so provides the desired property of intermittency. An individual sequence may then look like that shown in Fig. 1b. Note the intervals, e.g., after the first ramp gust, during which only zero gusts are occurring.

The "global intermittency" parameter F is set $0.0 \leq F < 1.0$. For $F = 0.0$ the intermittency is minimal, with the separate gusts becoming more prominent for increasing F (Fig. 2).

Simulation of Patchiness

Starting from Gaussian turbulence, patchy turbulence time histories of simulated turbulence can be obtained by utilizing the concept of amplitude-modulation of two independent Gaussian random processes. Consider the block diagram of Fig. 3. By means of multiplication, a Gaussian random process, $a(t)$, is amplitude-modulated by an independent Gaussian process of different scale, $b(t)$. A third independent Gaussian process, $c(t)$, is added to the process just mentioned to obtain probability density of the output turbulence velocities comparable to those measured in actual turbulence.[6]

$$w(t) = a(t)b(t)\frac{Q}{\sqrt{Q^2+1}} + c(t)\frac{1}{\sqrt{Q^2+1}}$$

where $a(t)$ is the Gaussian signal, output of filter H_a; $b(t)$ is the amplitude modulator, output of filter H_b; and $c(t)$ is the Gaussian signal, output of filter H_c. Filter transfer functions $H_{a,b,c}$ (for horizontal turbulence u_g):

$$H_{a,b,c} = \frac{1}{1+\tau_{a,b,c}s} K_{a,b,c}$$

$$\tau_a = (L_{g_u}/V_a)(R+1)$$

$$\tau_b = (L_{g_u}/V_a)[(R+1)/R]$$

$$\tau_c = L_{g_u}/V_a$$

$$K_{a,b,c} = \sqrt{2\tau_{a,b,c}/\pi}$$

so $\sigma_{a,b,c}$ equals 1, independent of τ.

The variance of $w(t)$ is

$$\sigma^2_{w(t)} = \sigma_a^2\sigma_b^2\frac{Q^2}{Q^2+1} + \sigma_c^2\frac{1}{Q^2+1}$$

As $\sigma_{a,b,c} = 1$, the variance of $w(t)$ equals 1 and is independent of Q.

Through the parameter Q a complete class of probability density distributions is defined. Any particular value of Q—which ranges from zero to infinity—determines a corresponding choice of the probability density function. The limiting cases are $Q=0$ and $Q=\infty$, corresponding to the Gaussian distribution and the so-called "Bessel distribution," respectively.

The ratio R between the cutoff frequencies of filter H_a and filter H_b in Fig. 3 affects neither the power spectral density $\phi_{ww}(\omega)$ nor the probability density function $p_w(x)$ of the output turbulence velocities. Varying this ratio R does, however, affect the characteristics of the output simulated turbulence. In fact the value of R determines the scale length of patchiness L_p relative to the integral scale length of turbulence L_g. As the ratio R decreases from $R=1$ to $R=0$ the "average patch length" increases ($L_p = L_g/R$).

NLR Turbulence Model

The NLR model is based on the RAE technique for generating intermittent signals. In order to further enhance the realism of this model there was the wish to add the character of patchiness to it. This patchiness should be generated in a simple way to save computation time and yet have all the desired properties. The most promising way seems to be the patchy rms modulation of an intermittent signal.

Reconsidering the simulation of patchiness, it is noticed that for relatively long patches ($R \ll 1$) the signals $a(t)$ and $c(t)$ are similar. This led to the idea that another approach to the generation of patchiness is possible by modulating a part of $c(t)$ (Figs. 4a and 5).

$$w(t) = c(t)\left\{(Q/\sqrt{Q^2+1})b(t) + 1/\sqrt{Q^2+1}\right\}$$

or

$$w(t) = c(t)m(t) \quad \text{for} \quad m(t) = \frac{1+b(t)Q}{\sqrt{Q^2+1}} \text{ (rms modulator)}$$

Transfer function H_b of patchiness filter:

$$H_b = K_b/(1+\tau_b s)$$

$$\tau_b = L_p/V_a = L_g/RV_a$$

$$K_b = \sqrt{2\tau_b/\pi}$$

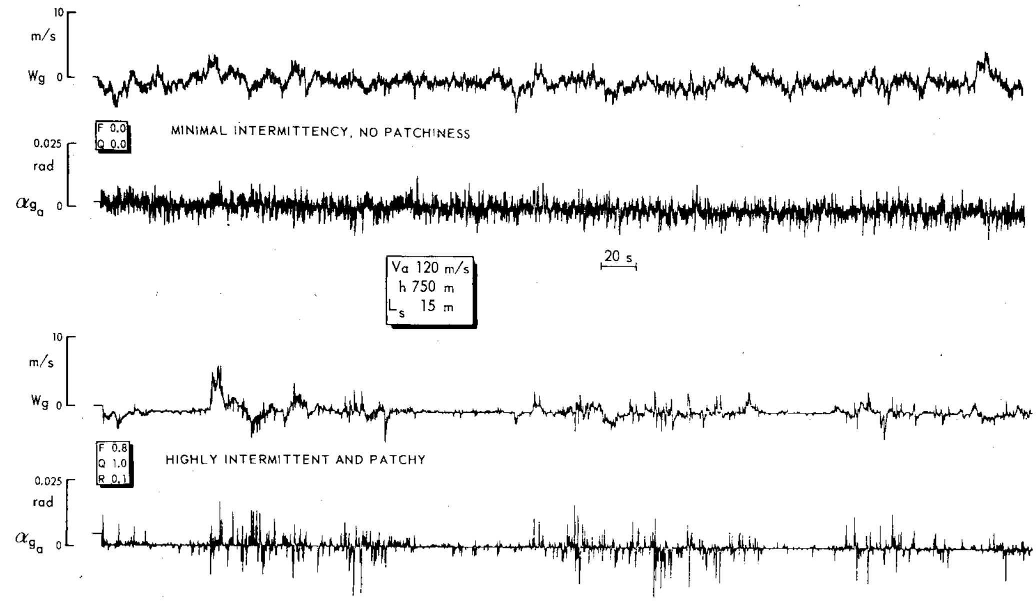

Fig. 6 Typical time histories of turbulence signals for "extreme" values of intermittency and patchiness.

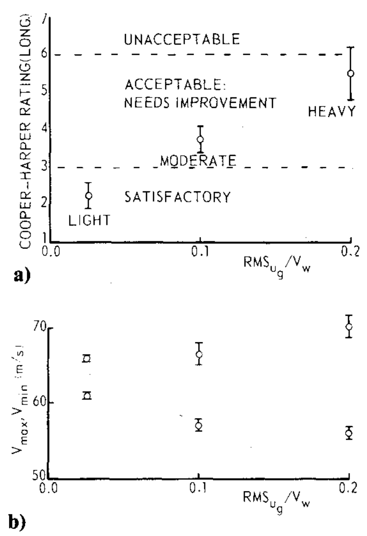

Fig. 7 a) Handling quality ratings vs longitudinal rms turbulence level; b) airspeed extrema vs longitudinal rms turbulence level.

If the Gaussian signal $c(t)$ is substituted by an intermittent signal $i(t)$ a turbulence velocity containing both intermittency and patchiness is the result (Fig. 4b).

$$w(t) = i(t)m(t)$$

Figure 6 shows time histories in which the different effects of patchiness and intermittency are clearly demonstrated.

Time histories of real-world turbulence show a correlation between the variation of the rms of the components. All turbulence velocities are influenced the same way by a patch. Therefore in this model one signal, $m(t)$, is generated to modulate the rms of all five turbulence velocities.

Evaluation Program

The four-degree-of-freedom moving base flight simulator of NLR was used to simulate a medium size twin-engine jet transport. This simulator provides motion cues in pitch, roll, yaw, and heave. An outside visual scene is generated via a television model-board system.

The piloting task was to capture a 3-deg ILS at 2100 ft altitude and perform an approach at 125 knots under IFR conditions using raw ILS data for guidance down to 300 ft. Flare and landing were performed under visual conditions. During all approaches a variable windshear with a windspeed decreasing from 30 knots at initial altitude to 15 knots at ground level was present.

After each run a pilot questionnaire had to be completed, while the computer calculated the performance (e.g., airspeed deviation) on-line. In the questionnaire the pilot had to indicate 1) the effort needed for aircraft control and ILS tracking, 2) turbulence realism, 3) patchiness of turbulence, 4) intermittency of turbulence.

After a session of 3 runs by means of a comment card the pilot was requested to

1) indicate a Cooper-Harper rating[1] for this aircraft under the simulated conditions;

2) make a comparison with a reference flight without turbulence;

3) comment on realism, intensity, patchiness, intermittency, and frequency content of the turbulence;

4) estimate type of weather and terrain related to the turbulence as experienced by the pilot.

During this program the settings of the turbulence model for 1) mean intensity, 2) intermittency, and 3) patchiness were varied, and were evaluated by the three participating pilots in a pseudorandom order.

Results

As the collection and analysis of the data are still in progress, some selected data for only one of the pilots are presented here.

Figure 7 shows the Cooper-Harper ratings and some performance data as a function of the longitudinal turbulence level for a turbulence simulation without patchiness ($Q=0.0$) and with moderate intermittency ($F=0.2$). The intensity has a major effect on all measured parameters and on the rating, and it was therefore decided to keep the intensity at a fixed moderate level ($\text{rms}_{u_g}/V_w=0.1$) during the remaining flights.

Variation of the "global intermittency" F does not have a consistent effect on subjective handling quality rating, although the performance (airspeed deviation) is degrading with increasing F (Fig. 8). The pilot rated the patchiness as too continuous, while his impression of intermittency shows a good correlation with the global intermittency F. The best realism rating is given for $F=0.4$-0.6.

In Fig. 9 the patchiness intensity Q is increased, while the intermittency is kept at the value $F=0.0$. The Cooper-Harper ratings show that for $Q=0.1$ and 0.2, poorer ratings are given than for $Q=0.0$ and 0.5, whereas the $Q=0.2$ and 0.5 cases give the best representation of actual turbulence according to the ratings given for the turbulence realism.

Based on the pilot opinions it was concluded that a combination of patchiness and intermittency might give the best realism. This is shown by evaluating the four models shown in

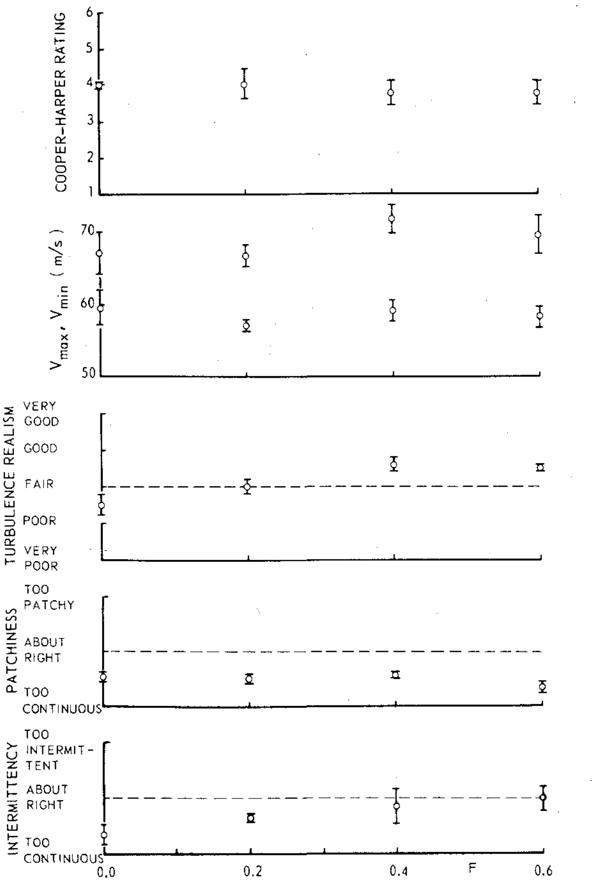

Fig. 8 Ratings and airspeed extrema vs "global intermittency" F ($Q=0.0$).

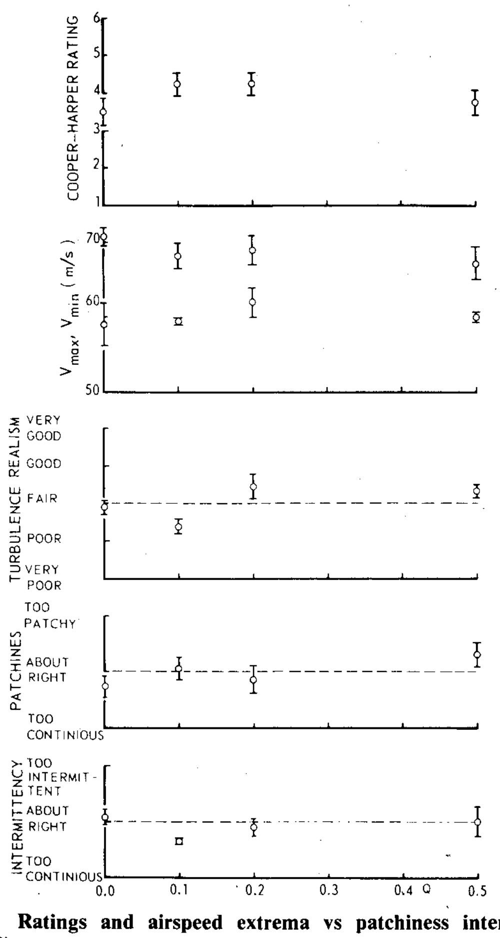

Fig. 9 Ratings and airspeed extrema vs patchiness intensity Q ($F=0.0$)

Table 3 Characteristics of four turbulence models

Model	F	Q	R	Description
1	0.0	0.0	...	Near-Gaussian
2	0.6	0.0	...	Intermittent
3	0.0	0.5	0.2	Patchy
4	0.2	0.3	0.4	Patchy and intermittent

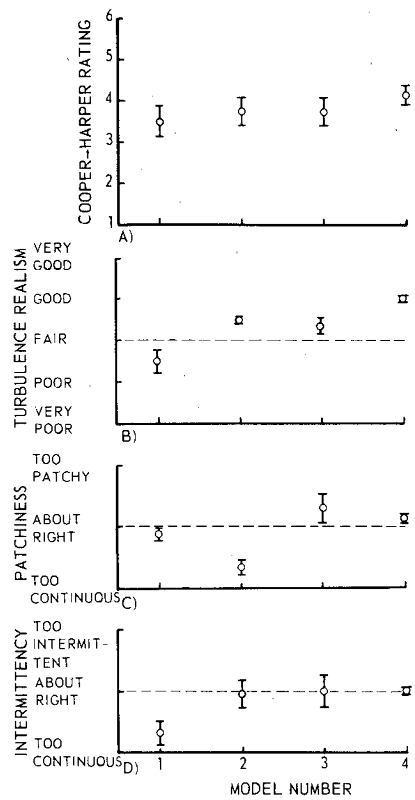

Fig. 10 a) Handling-quality ratings; b) turbulence realism; c) patchiness; d) intermittency.

Table 3. Figure 10 shows that the pilot opinion was in accordance with the setting of the turbulence model. The more complex model, No. 4, was considered to have a good realism, and it also has the greatest degrading effect on the handling qualities. This effect is not too big for the simulated aircraft with relatively good handling qualities, but a trend is indicated. The pilot opinion of the realism of turbulence improves from poor for the Gaussian model via fair for a model containing patchiness or intermittency to good for a model with both characteristics. So it is advisable to use a turbulence model with a combination of patchiness and intermittency. In the NLR model these effects are separately and independently controllable with known effects on the statistical parameters of the turbulence.

The results presented in this paper are based on three runs per turbulence setting for only one pilot. In a forthcoming report results of the full evaluation program and a more detailed description of the turbulence model will be given.

Conclusions

In future flight simulator studies on handling qualities it is recommended to apply a turbulence model that contains the effects of both intermittency and patchiness. As appears from the present study, the addition of these two effects increases the realism of the turbulence simulation and thus enhances the pilot acceptance of a simulation, while having a degrading effect on handling qualities. In combination with a correct choice of the mean turbulence intensity more real-life environmental conditions are created.

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