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On-Line Wind Shear Generation for Flight Simulator Applications

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A technique for generating on-line wind inputs for flight simulator applications has been developed. This approach yields wind inputs that are produced by a wind controller acting on the aircraft state and input vectors. The form of the wind controller is established off-line through an optimization process that selects its parameters so as to produce winds which represent some type of worst-case situation. Three such wind controllers were tested in a three degree-of-freedom fixed-base simulation of a light STOL transport. Data were collected for steep ILS approaches flown by two pilots, and an evaluation was made of the severity and realism of the generated winds. Comparisons were made with results obtained in the presence of two reference wind profiles. These tests indicate that the wind controller technique has several advantages over existing simulator wind modeling methods and that it should be assessed further in a more sophisticated flight simulator.

Nomenclature

d	= glide path deviation normal to glide path plane
h	= altitude AGL, m
q	= pitch rate, rad/s
T	= natural mode period, s
$T_{½(2)}$	= time to half (double) amplitude, s
u	= airspeed component along x stability axis
V_e	= reference equilibrium airspeed
W_1	= tail wind velocity, ms^{-1}
W_3	= downdraft velocity, ms^{-1}
W_{1e}	= reference equilibrium value of W_1, ms^{-1}
W_{1wc}	= contribution of wind controller to W_1
W_{3wc}	= contribution of wind controller to W_3
w	= airspeed component along z stability axis
x_1	= horizontal position
γ_G	= glide slope angle, deg
ζ	= damping ratio
θ	= Euler pitch angle, rad
μ_{Sws}	= mean of S_{ws}
σ_{Sws}	= standard deviation of S_{ws}
ω	= damped natural frequency
ω_n	= undamped natural frequency

Notation Conventions

X	= matrix
X^{-1}	= inverse of X
X^T	= transpose of X
$\hat{x}$	= mean of rms value of x
x	= vector or column matrix
$\Delta(\ )$	= perturbation quantity about a reference equilibrium value

Introduction

A NUMBER of landing approach and takeoff accidents in which variable winds have been found to be major contributing factors (e.g., the well-documented JFK accident in 1975) have focused attention on wind modeling for aircraft hazard definition.[1] From the perspective of flight simulator wind modeling, such hazardous wind conditions are best represented by discrete (i.e., deterministic) models. These may be generated using a number of techniques, including situation specific models based on the physics of atmospheric flows (i.e., thunderstorm outflow models[2]) and mathematically optimal worst-case methods.[3] The latter group of techniques seek wind disturbances constrained in a specified manner that maximize a functional of the state of the aircraft. They pose the worst-case concept in a formal mathematical framework while at the same time avoiding the difficult task of modeling complex atmospheric flows. Such techniques have been used in the past to find worst-case wind time histories (e.g., van der Vaart's method[3]).

For certain types of formulations it is possible to specify the worst-case solutions in terms of the aircraft state.[4] This technique is equivalent to closing the loop on the wind and appears to be well suited to flight simulator applications. The level of control difficulty caused by the presence of the variable winds may be adjusted by setting parameters within the wind controller. More importantly, because the human pilot introduces randomness and because the gross features of the control-loop signals are removed by linearizing about a reference equilibrium, the pilot will never see the identical wind profile twice and thus, as in the real world, each encounter will represent a new experience. It is apparent that this technique takes the form of a state feedback control law. The pilot in effect flies an aircraft with modified vehicle dynamics. Because the feedback control law actually employed is based on a wind shear scenario, one would expect the overall system to behave as a piloted aircraft under the influence of variable winds, provided that care was taken to insure that unrealistic wind levels were excluded. This is in fact the case. Pilots who have flown our flight simulator employing these wind controllers were convinced that they were executing a landing approach in the presence of wind shear.

In the following the results of a preliminary assessment of the wind controller method for flight simulator applications are presented. Three wind controllers synthesized using one- and two-sided (differential game) optimization theory were implemented on a manned three degree-of-freedom fixed-base simulation of a light STOL transport. Data were collected for steep ILS approaches flown by two pilots and an evaluation made of the wind model severity and realism. These results were then compared with others obtained in the presence of two reference wind profiles.

Theoretical Background

Two-sided optimization (conflict of interest) problems constrained by systems of differential equations are the subject of *differential games*.[5] In the broadest sense dif-

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ferential games are a subset of game theory and are related to it in much the same manner as optimal control theory is to functional minimization. A detailed development of the application of differential games theory to the aircraft controller vs wind conflict of interest problem is given in Ref. 4, thus only a few of the key steps in this development will be summarized here.

The conflict of interest between the wind and the aircraft controller is an example of a minimax problem. Such problems may be conceptually viewed as a conflict between intelligent adversaries and may be heuristically defined as follows. The payoff function

$$J[u(t),\eta(t)] = s[x(t_f),t_f] + \int_{t_0}^{t_f} g[x(t),u(t),\eta(t),t]\,\mathrm{d}t \quad (1)$$

is to be maximized by the disturbance vector $\eta \epsilon H$ and minimized by the control vector $u \epsilon U$ subject to the differential equations of motion

$$\dot{x}(t) = f[x(t),u(t),\eta(t),t] \quad (2a)$$

$$x(t_0) = x_0 \quad (2b)$$

Here t_0 is the initial time and t_f is the final or terminal time. The minimax solution to this problem, if it exists, satisfies the inequalities

$$J(u^*,\eta) \leq J(u^*,\eta^*) \leq J(u,\eta^*) \qquad \eta\epsilon H,\ u\epsilon U \quad (3)$$

The superscript asterisk denotes the minimax solution. u and η are subject to the constraints implied by the admissible control and disturbance spaces U and H, respectively. The payoff function J is defined in a way such that its minimization reflects good controller performance and its maximization reflects poor performance. The payoff function and the admissible control and disturbance spaces must constrain u and η sufficiently to make the problem meaningful, i.e., so that arbitrarily large control and disturbance input energies are not allowed.

With the notable exception of the class of linear quadratic problems, feedback solutions to minimax problems are generally difficult to obtain. For linear quadratic formulations the equations of motion are linear equations of the form§

$$\dot{x}(t) = Fx(t) + G_1u(t) + G_2\eta(t) \quad (4a)$$

$$x(0) = x_0 \quad (4b)$$

and the payoff function is quadratic, i.e.,

$$J = x^T(t_f)Sx(t_f) + \int_0^{t_f} [x^T(t)Qx(t) + u^T(t)R_1u(t) + \mu\eta^T(t)R_2\eta(t)]\,\mathrm{d}t \quad (5)$$

S and Q are positive semidefinite symmetric matrices, R_1 a positive definite symmetric matrix, and R_2 a negative definite symmetric matrix. The sign definiteness properties of these matrices make the problem meaningful in the minimax context. The positive parameter μ may be adjusted so that the disturbance "energy"

$$E = -\int_0^{t_f} \eta^T(t)R_2\eta(t)\,\mathrm{d}t \quad (6)$$

is within a desired range.

§For simplicity the linear quadratic problem will be presented as a time-invariant problem. The theory readily extends to time-varying cases.

The minimax feedback solution to the linear quadratic problem always exists for large enough values of the constant μ, and is given by

$$u^* = -R_1^{-1}G_1^TP(t)x(t) \quad (7a)$$

$$\eta^* = -\frac{1}{\mu}R_2^{-1}G_2^TP(t)x(t) \quad (7b)$$

$P(t)$ is the solution to the generalized matrix Riccati equation

$$\dot{P}(t) = -P(t)F - F^TP(t) + P(t) \times \left[G_1R_1^{-1}G_1^T + \frac{1}{\mu}G_2R_2^{-1}G_2^T\right]P(t) - Q \quad (8a)$$

$$P(t_f) = S \quad (8b)$$

The optimal value of J is given by

$$J^* = x_0^TP(0)x_0 \quad (9)$$

The Riccati equation (8a) is nearly identical to the Riccati equation that arises in linear quadratic optimal control problems, the difference being the $(1/\mu)G_2R_2^{-1}G_2^T$ term introduced by the minimax nature of the problem. If one wishes to consider a one-sided maximization, i.e., a minimax aircraft control law is not to be determined, then the worst-case control law continues to be given by Eq. (7b) where now the equations of motion [Eq. (4a)] do not contain control inputs u, the payoff function J of Eq. (5) does not contain the u^TR_1u term, and the Riccati equation (8a) does not contain the $G_1R_1^{-1}G_1^T$ term. One-sided maximization will be referred to as the *direct method.*

In the application to flight simulator wind modeling the Ricatti equation is solved off-line and the matrix $-(1/\mu)R_2^{-1} \cdot G_2^TP(t)$ is stored. This matrix may then be used in conjunction with Eq. (7b) to determine wind inputs in real time as the simulation proceeds. For the purposes of this preliminary study, however, time-invariant control laws based on a value of P at a suitably chosen time were used, thereby eliminating the need for large amounts of computer memory for storing a time-varying wind control law.

Aircraft Dynamics Model

The aircraft equations of motion are taken to be the longitudinal equations linearized about an equilibrium condition of constant airspeed flight along a rectilinear glide slope in the presence of a constant headwind. The control inputs are elevator angle δ_E in radians and throttle position δ_T expressed as a fraction of full throttle. These equations may be written in the matrix form[6]

$$\Delta\dot{x} = A\Delta x + C_1\Delta\delta + C_2\Delta W + C_3\Delta\dot{W} \quad (10)$$

where

$$\Delta x^T = [\Delta u \Delta w \Delta q \Delta\theta \Delta x_1 \Delta h] \quad (11)$$

$$\Delta\delta^T = [\Delta\delta_E \Delta\delta_T] \quad (12)$$

$$\Delta W^T = [W_1 - W_{1e}, W_3] \quad (13)$$

The detailed expressions for A, C_1, C_2, and C_3 are given in Ref. 4.

The simulated aircraft is a turbine powered twin-engined light STOL transport of 4500 kg (11,000 lb) gross weight. The linearization reference equilibrium conditions used were $V_e = 40\ \mathrm{ms}^{-1}$, $\gamma_G = 7$ deg, and $W_{1e} = 0$. The resulting modal characteristics are summarized in Table 1.

Table 1 Summary of natural mode characteristics with and without wind controllers

Wind model	Mode	ζ	ω_n, rad/s	ω, rad/s	$T_{1/2}$ or (T_2), s	T, s
Open-loop	Short-period	0.651	2.56	1.94	0.416	3.24
Open-loop	Phugoid	0.175	0.298	0.293	13.3	21.4
3	Phugoid	−0.340	0.321	0.302	(6.36)	20.8
4	Phugoid	−0.255	0.453	0.438	(6.00)	14.3
5	Phugoid	−0.157	0.391	0.386	(11.3)	16.3

The equations of motion (10) were used for the flight simulator dynamic model but had to be rewritten in the form of Eq. (4a) in order to apply the minimax theory described in the previous section. For the worst-case wind controllers used in this study, a suitable form can be shown to be[4]

$$\Delta\dot{x}_{op} = A_{op}\Delta x_{op} + C_{1op}\Delta\dot{\delta} + C_{3op}\dot{W}_{wc} \tag{14}$$

where

$$\Delta x_{op}^T = [\Delta u \Delta w \Delta q \Delta\theta \Delta\delta_E \Delta\delta_T] \tag{15}$$

$$\dot{W}_{wc}^T = [\dot{W}_{1wc}\dot{W}_{3wc}] \tag{16}$$

Here Δx_{op}, $\Delta\dot{\delta}$, $\dot{W}_{wc}$, A_{op}, C_{1op}, C_{3op}, have a one-to-one correspondence with $\boldsymbol{x}$, $\boldsymbol{u}$, $\boldsymbol{\eta}$, $\boldsymbol{F}$, $\boldsymbol{G}_1$, and $\boldsymbol{G}_2$ of Eq. (4a). The control inputs are the elevator rate $\dot{\delta}_E$ and the throttle rate $\dot{\delta}_T$. This permits the elevator deflection and throttle position to be treated as part of the state vector, allowing wind controller solutions that take pilot control actions into account when determining the worst-case wind inputs. The Δx_I and Δh components of the state vector Δx of Eq. (11) are dropped from Eq. (15) because they are not treated as being available to the wind controller. $\dot{W}_{1wc}$ and $\dot{W}_{3wc}$ are, respectively, the wind controller contributions to the $\dot{W}_1$ and $\dot{W}_3$ components of the wind vector. Since W_1 and W_3 appear only in the Δx_I and Δh equations (see Ref. 6) they also drop out of Eq. (14).

Wind Models

Five wind models were used in this study. Two of these were fixed reference profiles while the remaining three were wind controller models based on the intelligent adversary concept and synthesized using the linear quadratic theory. No turbulence inputs were introduced in any of the runs.

Model 1 is a constant shear (0.75 ms^{-1}/30 m) profile representative of light wind shear conditions in which $W_3 = 0$ (see Fig. 1). It was used to obtain baseline data.

Model 2 (Fig. 1) is based on the winds estimated to be present at the time of the JFK accident. The downdraft velocities were reduced by a factor of 0.75 to make them more compatible with the climb capabilities of the simulated STOL transport. This model was used to obtain data representative of flight in extreme wind shear and downdraft conditions.

Models 3-5 are the wind controller models. The payoff function weighting matrices [see Eq. (5)] under which they were obtained were diagonal and are defined in Ref. 4. The weights were selected so that technically significant deviations in the aircraft state from the reference state were weighted approximately the same and so that the phugoid mode of the aircraft was destabilized (see Table 1). At the present time no formal algorithm for determining these weights has been developed. The values selected for the present application were obtained by a series of trial-and-error interactions with the computer. The wind inputs generated by these models were introduced at an altitude of 400 m (1300 ft) and were superimposed on the wind profile of model 1. The latter was done to facilitate comparisons with the baseline data.

For certain situations (e.g., unusually large airspeed deviations), the wind inputs generated by the wind controllers may become unrealistically large. This problem was avoided

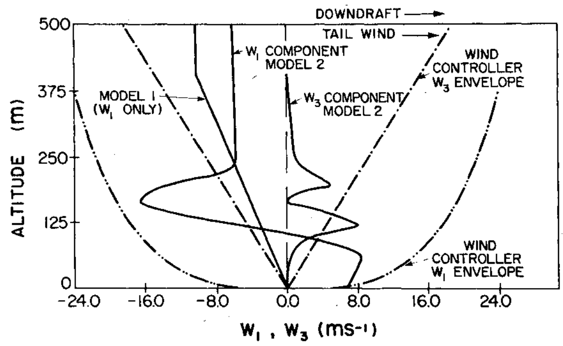

Fig. 1 Reference wind profiles and wind speed envelopes.

by specifying wind speed envelopes as shown in Fig. 1. The wind inputs were matched smoothly with these envelopes using an algorithm that was applied continuously to $\dot{W}_1$ and $\dot{W}_3$. This algorithm was based on the ratio of the square of the acutal wind speed to the square of the wind envelope speed.

There is no guarantee that the human pilot will attempt to minimize the same payoff function that the wind controllers are trying to maximize or that he will even perform optimally. Furthermore, the wind controller optimization did not take into account the presence of the baseline wind profile and the wind speed envelopes. All of these factors make the wind controllers suboptimal, i.e., they are not mathematically worst-case for the simulated flight task. From the practical point of view, however, these differences between the dynamic system for which the wind controllers were optimized and the actual dynamic system to which they were applied were not found to reduce the perversity of the wind controller models to such an extent that it prevented their application to hazardous wind modeling on flight simulators, as will be demonstrated in the following section.

The wind control law for model 3 is given by

$$\dot{W}_{1wc} = -0.299\Delta u - 0.00722\Delta w + 0.326\Delta q + 1.08\Delta\theta$$
$$+ 0.821\Delta\delta_E - 0.730\Delta\delta_T \tag{17}$$

$$\dot{W}_{3wc} = 0.0136\Delta u - 0.040\Delta w + 0.143\Delta q + 1.46\Delta\theta$$
$$- 0.834\Delta\delta_E - 0.0344\Delta\delta_T \tag{18}$$

This is based on a steady-state minimax solution¶ and includes contributions that depend on $\Delta\delta_E$ and $\Delta\delta_T$, i.e., the pilot's control actions are taken directly into account in determining the worst-case wind inputs.

The wind control law for model 4 does not have W_3 components nor $\Delta\delta_E$, $\Delta\delta_T$ feedback, a formulation that was found to be particularly effective in destabilizing the open-loop phugoid mode of the aircraft. It is based on a direct method worst-case solution with $\boldsymbol{P}(t)$ in Eq. (7b) replaced by **

¶Wind control law [Eq. (7b)] with $\boldsymbol{P}(t)$ replaced by $\lim_{t\to-\infty} \boldsymbol{P}(t)$ (see Ref. 4).

**Because of the presence of conjugate points (see Ref. 4), this model did not have a steady-state solution. The wind control law was arbitrarily chosen to be that control law which results from Eq. (7b) with $\boldsymbol{P}(t)$ replaced by $\boldsymbol{P}(0)$.

$P(0)$ and is given by

$$\dot{W}_{1wc} = -0.365\Delta u - 0.195\Delta w + 2.19\Delta q + 12.9\Delta\theta \qquad (19)$$

Model 5 is of the same type as model 4, but it is somewhat less destabilizing of the phugoid mode (see Table 1). It is given by

$$\dot{W}_{1wc} = -0.244\Delta u - 0.106\Delta w + 1.20\Delta q + 7.08\Delta\theta \qquad (20)$$

Description of Experiment

The STOL transport's dynamic characteristics and the wind models were implemented on the UTIAS multipurpose fixed-base simulation facility. Cockpit instrumentation consisted of an airspeed indicator, an altimeter, an engine power indicator, and an electronic attitude indicator with fast-slow and glide path deviation bugs. The controls available were elevator, throttle, and pitch trim. No out-the-window visual cues were presented to the pilots. All simulation variables were updated and sampled at 25 Hz, and recorded on digital magnetic tape.

The simulated task consisted of intercepting a 7 deg ILS glide path from level flight at 460 m (1500 ft) and flying an approach to a 60 m (200 ft) decision height. Pilots were instructed to fly the approach using whatever technique they felt was appropriate, but in all circumstances to continue to the decision height.

Two pilots participated in the study. Subject 1 was an experienced (13,000 h total time) test pilot with over 1000 h IFR and 400 h in flight simulators. Subject 2 was a civilian flying instructor (950 h total time) with 29 h IFR and 9 h in flight simulators.

The pilots were briefed on the approach task and then flew familiarization runs with practice variable wind conditions consisting of a W_1 time-referenced sinusoid at the phugoid frequency until they felt comfortable with the simulation. Production runs were flown in blocks of five approaches, each block utilizing the same wind model, for a total of 10 runs per wind model per pilot. The order of the blocks was randomized for each pilot. Prior to flying the production runs each pilot was told that he would encounter variable wind conditions but was not informed as to the type and degree of severity of the winds.

Following each approach the pilot was asked to fill out a questionnaire. After each block of five approaches he was interviewed by the experimenters to elicit any further comments regarding the winds encountered and the simulation itself.

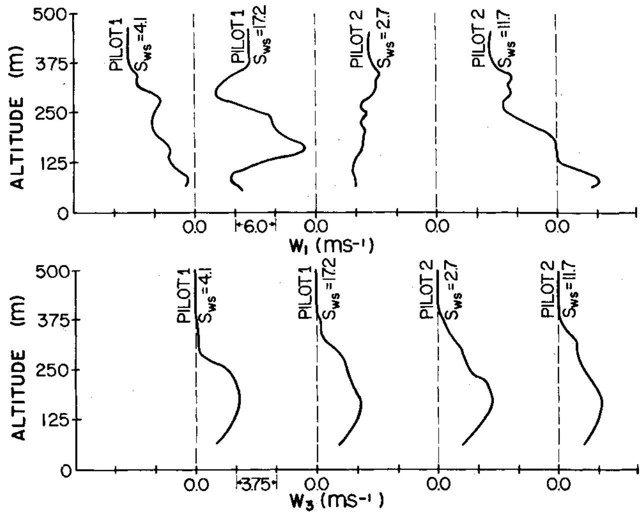

Fig. 2 Wind model 3.

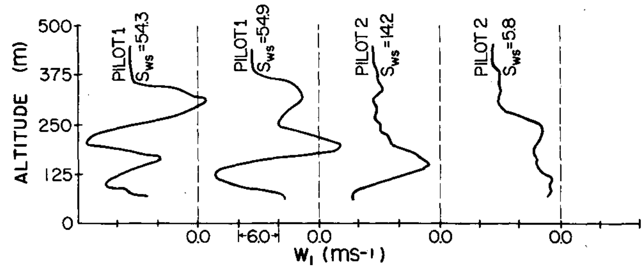

Fig. 3 Wind model 4.

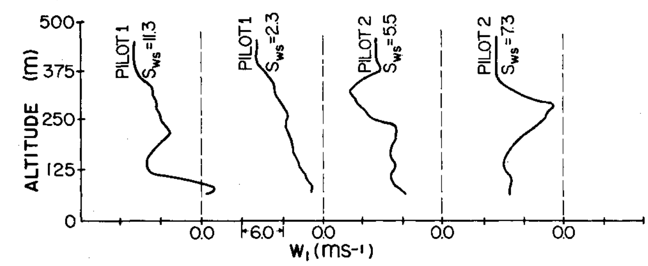

Fig. 4 Wind model 5.

Results and Discussion

The data recorded during the production runs included all of the longitudinal state variables, as well as the control variables and wind inputs. Root-mean-square values of these were computed for the runs and the values were analyzed (using t tests) to determine whether significant differences existed with respect to the baseline (model 1) results and between pilots.

Figures 2-4 contain a representative sampling of the wind profiles that were obtained from the three wind controller models. Other than the W_3 inputs of model 3, the profiles change markedly from run to run and pilot to pilot.

The relatively minor changes observed in the characteristics of the W_3 profiles of model 3 may be explained by considering in detail the way in which the wind controllers were synthesized and then implemented in the simulation. In the optimal wind controller synthesis process, a linear aircraft dynamics model with $W_{1e} = 0$ and time-invariant reference equilibrium conditions was used. In the simulation the same aircraft dynamics model was used but the wind inputs generated by the wind controller were superimposed onto the linear wind profile of model 1. In general the presence of the linear wind results in $\Delta\theta$ and $\Delta\delta_T$ offset components that feed back through the wind controller model to generate W_1 and W_3 offsets. This effect was most prominent for W_3 in model 3, a consequence of the particular values of the $\Delta\theta$ and $\Delta\delta_T$ gains in that model, and resulted in a significant contribution to W_3 that was unchanged from run to run.

This characteristic can be avoided by deleting the linear wind or by considering a more sophisticated simulation in which the state variables that produce these offset effects are passed through a suitably defined low-pass filter. The perturbation quantities $\Delta\theta$, $\Delta\delta_T$, and so forth on which the wind controller operates can then be defined with respect to the filtered quantities rather than with respect to their reference equilibrium values, thus eliminating the unwanted offsets in the wind controller output.

The wind variability was measured by the quantity

$$S_{ws} = \int_0^{t_f} [\dot{W}_1^2(t) + \dot{W}_3^2(t)]\,dt \qquad (21)$$

This quantity is analogous to the integral E of Eq. (6). t_f was in the range $90 \le t_f \le 105$ s for all of the runs, but showed less

Table 2 S_{ws} summary for all wind models

	Pilot 1			Pilot 2		
Wind model	μ_{Sws}, $m^2 \cdot s^{-3}$	σ_{Sws}, $m^2 \cdot s^{-3}$	σ_{Sws}/μ_{Sws}	μ_{Sws}, $m^2 \cdot s^{-3}$	σ_{Sws}, $m^2 \cdot s^{-3}$	σ_{Sws}/μ_{Sws}
1	0.9	0.0	0.0	0.9	0.0	0.0
2	127.7	15.0	0.12	104.7	20.8	0.20
3	10.3	4.8	0.47	5.1	3.0	0.59
4	111.8	43.2	0.39	12.4	5.2	0.42
5	5.8	2.8	0.48	5.2	2.1	0.40

Table 3 ICAO wind shear classification

Category	Vertical shear magnitude $ms^{-1}/30$ m
Light	0-2.5
Moderate	2.5-4.5
Strong	4.5-6.0
Severe	>6

variation for runs involving a particular wind model. S_{ws} depends on the time rate of change of the wind velocity as seen by the aircraft, and will thus change from run to run even for runs in the presence of the reference profiles of models 1 and 2.

As well as producing different wind inputs from run to run, the wind controller models also showed considerable S_{ws} variation both among the wind models and between pilots. This is apparent from Table 2. The quantity σ_{Sws}/μ_{Sws} is generally larger for the wind controller models than for the fixed profiles of models 1 and 2. Also, the S_{ws} values for models 2-5 are generally larger for pilot 1 than for pilot 2.

For models 2-4 these differences in μ_{Sws} between pilots were shown to be significant at the 5% confidence level (see Table 5). This suggests that some fundamental differences existed in the control strategies adopted by the two pilots. Since the wind controllers determine wind inputs based on a subset of the aircraft state and control inputs, certain control strategies will therefore produce different wind characteristics. This is also suggested by a comment, repeated several times by pilot 1, that he concentrated on obtaining good glide path tracking and was willing to tolerate a "few knots" of airspeed deviation. Since none of the wind controller models contain glide path deviation in their wind generation algorithms while they all contain airspeed deviation, they would tend to produce less severe winds for pilots who adopted a tighter airspeed tracking strategy. Conversely, a pilot who adopts a tight glide path tracking strategy at the expense of airspeed tracking might ultimately find himself in a divergent situation where both airspeed and glide path tracking performance are degraded markedly. Such an effect was seen for pilot 1 during many of his approaches involving model 4 where the wind inputs would oscillate from one side of the limiter envelope to the other.

The hazard posed by the wind controller models was evaluated using a number of techniques, including the following:

1) Comparison of S_{ws} values obtained for the wind controller models with those obtained for the fixed profile of model 2, which is known to be extremely hazardous to aircraft.

2) Categorization of the wind shear encountered for a given W_l profile in 30 m altitude increments according to the ICAO interim classification[7] of Table 3.

3) Subjective evaluation through the pilots' response to the questionnaire.

Each of these will be discussed briefly in the following.

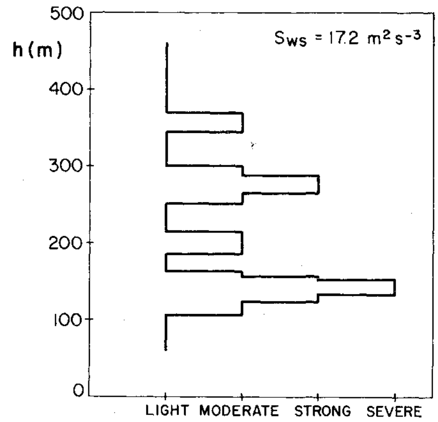

Fig. 5 Shear classification of second W_l profile of Fig. 2.

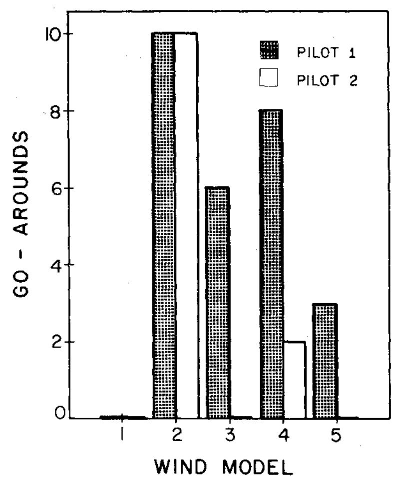

Fig. 6 Number of approaches (out of 10) which would have been aborted.

In general the S_{ws} values that were obtained for the wind controller models were smaller than those obtained for model 2. These generally smaller values do not necessarily imply that the winds generated by these models are not hazardous. S_{ws} represents an average value of wind variability; large shears may still have existed even in runs where S_{ws} was not large. As an example of this the second W_l wind profile of Fig. 2 has been categorized as to shear strength according to the ICAO classification of Table 3. From Fig. 5 it is seen that despite the relatively small value of S_{ws}, there are a number of strong and severe shear encounters.

The pilots' assessment of the wind hazard through the questionnaire also produced some interesting differences between them. For all of the wind models, as compared to pilot 2, pilot 1 generally rated the winds encountered as being more hazardous, the flight task as being more difficult, and the aircraft controllability as being more marginal. As an example of this trend Fig. 6 shows the number of go-arounds

Table 4 Statistics summary[a]: Rise in mean rms values for wind models 2-5 over baseline (model 1) runs

Wind model	Pilot 1 $\Delta\hat{u}$	$\Delta\hat{d}$	μ_{Sws}	$\hat{\dot{\delta}}_T$	$\hat{\dot{\delta}}_E$	$\Delta\hat{u}$	$\Delta\hat{d}$	μ_{Sws}	$\hat{\dot{\delta}}_T$	$\hat{\dot{\delta}}_E$
2	21.0[b,c]	14.5[c]	18.9[c]	1.6	7.8[c]	4.0[c]	5.87[c]	15.7[c]	2.43[c]	8.5[c]
	(4)	(4)	(4)	(8)	(5)	(9)	(9)	(9)	(13)	(10)
3	8.0[c]	3.78[c]	6.3[c]	0.36	4.6[c]	3.0[c]	3.0[c]	4.67[c]	0.57	4.0[c]
	(10)	(12)	(9)	(11)	(13)	(13)	(17)	(9)	(12)	(9)
4	10.7[c]	4.35[c]	8.1[c]	2.0[d]	7.5[c]	7.0[c]	1.0	7.18[c]	1.0	12.0[c]
	(9)	(9)	(9)	(17)	(11)	(10)	(15)	(9)	(10)	(15)
5	4.0[c]	0.83	5.4[c]	−0.82	0.67	5.0[c]	−0.3	6.1[c]	1.14	11.0[c]
	(13)	(13)	(9)	(10)	(17)	(13)	(16)	(9)	(15)	(13)

[a]Based on one-tailed t tests for two populations having different and unknown variances, testing H_0: the mean rms values for wind model runs are equal to those for the baseline runs. [b]t value/(degrees of freedom). [c]Significant at the 0.025 level. [d]Significant at the 0.05 level.

that each pilot felt should have been executed if this had been allowed. Pilot 1's greater number of go-arounds is compatible with the larger S_{ws} values that he obtained for many of the wind controller runs. We note, however, that even for model 5, for which the S_{ws} mean and standard deviations for the two pilots were similar (see Table 2), pilot 1 would still have executed a greater number of go-arounds.

Both pilots had difficulty determining the type of wind disturbance (i.e., W_1, W_3, or both) which they had encountered on a given approach. Pilot 1 commented that he would have been able to make a better assessment of the type of wind inputs if inertial acceleration cues had been available.

Both pilots generally found the wind controller models useful for training purposes, although for some of the runs they found the winds that they had encountered to be unrealistically severe. We note that the fixed profile of model 2, which is based on an estimate of the severe variable wind conditions that existed during the JFK incident, was also rated as being unrealistic for many of the runs.

t tests were employed to examine the differences between the results produced by wind models 2-5 and the baseline (model 1) and the differences between the two pilots. These tests were performed on the mean value of the rms response averaged over the 10 runs per subject for each wind model (except for pilot 1, model 1 for which only five runs were obtained). The results are summarized in Tables 4 and 5. From Table 4 it can be seen that with few exceptions significantly larger values of the rms levels were obtained for wind models 2-5 than for model 1. The least increase in rms level was found for throttle rate activity. From Table 5 it can be seen that pilot 1 produced significantly larger rms values for most variables than pilot 2, as is indicated by the positive values for the t statistic.

Summary and Recommendations for Future Work

Hazardous wind generation based on the intelligent adversary concept and implemented as wind controller models has been evaluated on a fixed-base flight simulator. The major advantage over prerecorded deterministic models is that this technique produces wind inputs that change from run to run and pilot to pilot. These low-frequency wind inputs tend to excite the more weakly damped low-frequency modes of the pilot-aircraft system, and thus are useful for hazard definition.[3,8] The wind controller models were generally considered by the pilots to produce disturbances that are useful for training purposes. Furthermore, some of the results suggest that the wind controller models may be formulated in a manner that favors certain pilot control strategies over others. This characteristic may ultimately prove to be useful as a training tool.

It is recommended that future work in this area should be undertaken to study:

1) The implementation and assessment of the wind controller technique on more sophisticated six degree-of-freedom moving base flight simulators.

Table 5 Statistics summary[a]: interpilot comparison of mean rms values for wind models

Wind model	$\Delta\hat{u}$	$\Delta\hat{d}$	μ_{Sws}	$\hat{\dot{\delta}}_T$	$\hat{\dot{\delta}}_E$
1	2.0[b]	3.8[c]	[d]	0.3	9.1[c]
	(18)	(17)		(14)	(10)
2	3.5[c]	5.7[c]	2.4[e]	1.1	8.9[c]
	(13)	(12)	(10)	(4)	(5)
3	4.0[c]	4.6[c]	2.9[e]	0.8	6.1[c]
	(13)	(10)	(15)	(16)	(15)
4	8.3[c]	4.9[c]	7.2[c]	2.7[e]	8.9[c]
	(12)	(10)	(9)	(9)	(9)
5	0.0	3.7[c]	0.5	−2.6[e]	5.3[c]
	(18)	(11)	(16)	(14)	(15)

[a]Based on two-tailed t statistics for two populations having different and unknown variances, testing H_0: the mean rms values for each wind model are the same for each pilot. [b]t value/(degrees of freedom). [c]Significant at the 0.01 level. [d]Indeterminate because $t = 0/0$. [e]Significant at the 0.05 level.

2) The level of pilot adaptation to wind controller models as compared with the learning effects associated with prerecorded deterministic models.

3) The development of real time techniques for controlling the level of wind variability and pilot workload for a given wind controller model.

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