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ANALYSIS OF RESPONSE TO WIND-SHEARS USING THE OPTIMAL CONTROL MODEL OF THE HUMAN OPERATOR*

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ABSTRACT

The effects of wind-shears on the approach performance of a STOL aircraft are analyzed using the optimal-control model of the human operator. This analysis involves a time-varying situation that is more complex than is traditionally treated by human operator modelling techniques. The extensions to the time-varying case are discussed and results are presented that illustrate the effects of wind shears on category II window-performance and the effects on performance of pilot time-delay and of variations in pilot gain during approach.

1. INTRODUCTION

In an instrument approach-to-landing the pilot attempts to maintain his position on the glide-path in the presence of external disturbances. An important part of the task involves compensation for errors introduced by winds. Most analytic studies of the problem based on human operator models have considered only the effects of zero-mean, random turbulence. However, winds with a non-zero mean component can be quite significant and may provide the dominant problem. These "mean-winds" generally vary with altitude. The rate of change of wind speed with altitude is called the shear variation and the altitude dependent winds are often refered to as wind-shears. The mean-wind can be described in statistical terms, i.e., the wind direction and speed are, in general, random variables. However, in a given approach-to-landing, a specific "sample" mean-wind is encountered. It is the response to particular samples that is usually of interest, rather than the response to the distribution as a whole.

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The introduction of wind shears into the approach problem complicates the situation considerably from the standpoint of analysis by human operator modelling techniques. The disturbance input no longer has stationary statistics and, furthermore, one expects the pilot to be capable of some "prediction" or other high level adaptation with respect to the shear variation. These two factors tend to compromise the theoretical and experimental bases for most quasilinear describing function models [1], although interesting attempts have been made to extend those models to quasi-predictable inputs [2].

Here, the optimal control model of the human operator [3] is used to analyze approach in a wind-shear environment. It is relatively straightforward, theoretically, to apply the optimal control model to this problem, because of the model's time domain foundation and its normative nature. This was demonstrated in a previous application to time-varying approaches involving constant updrafts [4]. That study also showed that model results were reliable predictors of experimental data for the time-varying situations analyzed.

This paper is an extension of the analysis presented in [4]; specifically, a more general class of disturbances is considered, and some time-varying facets of the optimal control model are examined in greater detail. The results are believed to be of interest both in terms of predicting the effects of wind-shears on approach performance and in leading to further understanding of human operator modelling techniques based on optimal control. On the other hand, unlike [4], experimental data to confirm or reject the model results are, unfortunately, not available at this time.

The paper begins with a brief discussion of the modifications to the human operator model required for analysis of the response to wind shears. Then, results are presented for a STOL approach that illustrate: (1) the effects of wind shears on performance at the approach "window"; (2) the effect of pilot time-delay on performance; and (3) the effects of changing pilot gain during approach. A more detailed presentation of the ideas and results may be found in [5].

2. MODIFICATIONS OF OPTIMAL CONTROL MODEL FOR TIME-VARYING DISTURBANCES

Consider the linear dynamic system

$$\dot{\underline{x}} = \underline{A}\,\underline{x} + \underline{B}\,\underline{u} + \underline{E}\,\underline{w} + \underline{F}\,\underline{z} \qquad (1)$$

where $\underline{x}$ is a vector representing the system state, $\underline{u}$ is a vector of control inputs, $\underline{w}$ is a vector of zero-mean, gaussian, white noises, $\underline{z}$ a vector of time-varying input disturbances and $\underline{A}$, $\underline{B}$, $\underline{E}$ and $\underline{F}$ constant matrices of appropriate dimension. We assume that $\underline{z}$ satisfies

$$\dot{\underline{z}} = \underline{A}_z \underline{z} \; ; \; \underline{z}(t_o) = \underline{z}_o \tag{2}$$

with $\underline{A}_z$ a constant matrix. (Note that if $\underline{E} = \underline{F}$ then $\underline{z}$ can be used to model a mean component of $\underline{w}$.) Various disturbance inputs may be generated from the model of Equation (2), particularly if impulses or jumps in "initial conditions" are allowed [6].

To examine how the control structure of the optimal control model is modified to account for the disturbance (2), we ignore the limitations on the human's observation processes, (time-delay and observation noise) and assume the $\underline{A}_z$ and $\underline{z}(t_o)$ are known. This implies the disturbance-state, $\underline{z}(t)$, is known for all t. This assumption is unrealistic and is made here only for expository reasons; in applying the model, $\underline{z}(t)$ is estimated from the available noisy, delayed data, as are the other system states.

The operator's control $\underline{u}$ is assumed to be chosen to minimize the quadratic cost functional

$$J = \lim_{T\to\infty} E\left(\frac{1}{T}\int_0^T \underline{x}'\underline{Q}\,\underline{x} + \underline{u}'\,\underline{R}\,\underline{u} + \dot{\underline{u}}'\underline{G}\,\dot{\underline{u}}\right)dt \tag{3}$$

where $\underline{Q}$ and $\underline{R}$ are positive, semi-definite matrices and $\underline{G}$ is positive definite. The solution to this problem is well-known and is developed in detail in the control literature [6-8]. In particular, it can be shown that the optimal control law satisfies

$$\underline{T}_N(t)\dot{\underline{u}}^* + \underline{u}^* = -(\underline{L}(t)\underline{x} + \underline{K}(t)\underline{z}) \tag{4}$$

where $\underline{T}_N$, $\underline{L}^*$ and $\underline{K}$ are time-varying matrices that are obtained by solving an appropriate matrix Ricatti equation (see [8] and [3] for details). Moreover, if the input disturbance does not have an exponentially growing component (i.e., if the eigenvalues of $\underline{A}_z$ are ≤ 0), the control gains in (4) approach a constant as $T\to\infty$. Thus, when the system matrices and cost functional weightings are time-invariant and when T is large relative to system time-constants, we may take advantage of

the enormous simplification afforded by a constant gain solution.* Under these conditions Equation (4) may be written as

$$\underline{u}^* = -(\underline{T}_N s + \underline{I})\;(\underline{L}^*\underline{x} + \underline{K}\,\underline{z}) \tag{5}$$

where $\underline{T}_N$ and $\underline{L}^*$ are identical to the neuro-motor lag and optimal feedback gain matrices obtained for the optimal control model of the human operator under stationary conditions [3]. Thus, the modification to the basic model to account for the time-varying, mean disturbance is a set of feedforward gains acting on the (estimate of) the disturbance.** This result, which is a direct consequence of the normative assumption, is satisfying intuitively and is not inconsistent with the "Successive Organization of Perception" concepts discussed in, e.g., [9].

As mentioned previously, $\underline{z}(t)$ is to be estimated from the available observation data. In terms of the estimation problem, it will be assumed here that the initial condition $\underline{z}_o$ is a gaussian random variable with known mean and variance. Thus, $\underline{z}(t)$ is gaussian and its distribution is known, for all t. The actual value of $\underline{z}(t)$ corresponding to a specific sample disturbance from the distribution is not known and is estimated from the displayed variables by means of a Kalman filter. It can be shown [5] that if the sample path does not correspond to the path generated by the mean of $\underline{z}_o$, then the error and the estimate are correlated, the filter being optimal only in terms of the distribution of $\underline{z}_o$. The expressions used to compute the corresponding estimation errors for this case are developed in [5].

Finally, it is important to note that the man-machine system response to a sample disturbance $\underline{z}(\cdot)$ is a random variable, even when $\underline{w} \equiv 0$. The reason for this is the human operator's randomness which is reflected in the observation and motor noises of the optimal control model.

*Actually, the "solution" may not be a solution at all, in that the infinite-time cost may be unbounded. However, this is a minor inconvenience that can be circumvented readily in applying the results [5, 7].

**An alternative, perhaps less satisfying, interpretation is that the control law involves integral as well as proportional feedback [6, 8].

3. ANALYSIS OF APPROACH PERFORMANCE

3.1 Approach Scenario

We consider the longitudinal approach of an Augmentor Wing Jet STOL Research Aircraft (AWJSRA), the C-8M.* The aircraft is assumed to be initially on the nominal (7.5 deg.) glide-slope with a nominal airspeed of approximately 31 m/s. Linearized perturbation equations were used to describe the aircraft motion. The pilot was assumed to control elevator and "nozzle" (thrust vector) in a continuous manner, whereas throttle was assumed to be fixed at the appropriate trim setting. The corresponding equations of motion, in state variable form, are given in [5].

The basic scenario for the analysis of longitudinal approach performance involved starting at an initial range of 1500m with a constant wind velocity corresponding to the value h = 125m (R ≈ 1160m). In all cases, turbulence having the Dryden spectral form [10] was assumed present. The scale-lengths of the turbulence were not varied with altitude; they were set at the constant value appropriate to the decision height. Gust intensities corresponded to a value that would not be encountered more than 10% of the time, i.e., a fairly severe condition.

The pilot's display was the EADI status display used in the STOLAND program [11] and described in another paper presented at this conference [12]. The STOLAND-status display shifts from an angular presentation of glide-path error to a height presentation at Range ≈ 575m (h ≈ 75m ≈ 250 ft.). The model for the human operator takes this variation in display gain into account by modifying appropriate observation parameters. Values for the parameters of human operator model were the same as those used for a corresponding steady-state analysis of performance at the decision height and are given in [5] and [12]. Suffice to say, that the values for parameters corresponding to human limitations were essentially the same as in previous studies [3, 4] and task-related parameters were determined from analysis of this problem [5, 12].

In addition to the above "basic" condition, the effects of variation in pilot gain were analyzed. It had been noted in [4] that the pilot might vary his gains so as to tighten control as the decision-height was approached. An analogous result can be obtained with the model by making the cost functional weightings of Equation (3) range-dependent. Indeed, if it is assumed that the pilot attaches a fixed penalty to angular deviations from the glide-path, rather than to linear deviations, then the weighting on height-errors will be range-dependent. We investigated two conditions with respect to this "gain-scheduling":

1. Constant Gains in which the cost functional weightings were constant and corresponded to Category II "window" performance requirements at the decision height.

2. Varying Gains in which angular glide-path error tolerances were assumed to be constant (corresponding to the allowable Category II window error). For this case, weightings (and, hence, gains) were changed in three stages according to the following schedule:

$$1500 \le R \le 1160\text{m} \;:\; q_h = .0029,\; q_{\dot h} = .0326$$
$$1160\text{m} \lessapprox R \lessapprox 575\text{m} \;:\; q_h = .0117,\; q_{\dot h} = .133$$
$$575\text{m} \lessapprox R \lessapprox 230\text{m} \;:\; q_h = .073,\; q_{\dot h} = .83$$

Thus, the weighting over a range-interval corresponded to the weighting appropriate to the end-point of that interval, a conservative choice. The intervals were chosen, as a matter of convenience, so that the end-points corresponded to points where other changes in the approach scenario were required.

A limited examination of the effect of pilot time delay was also conducted. It was expected that the human's time delay would increase scores but would not alter the basic character of the results. Because inclusion of the time delay increases significantly the costs of the time-varying computation, we decided to assume the time delay was zero. However, a comparison case was obtained with a time delay of .2 sec. (the nominal value found in previous studies) to illustrate the differences one might expect from including time delay.

3.2 Modelling the Wind-Shears

In modelling wind-shears both dynamic and kinematic effects should be considered. In addition, from the standpoint of the optimal control model, it is desirable (though not necessary) to convert the altitude dependence of the shear to an equivalent time dependence. In this section, kinematic effects of wind shears are modelled as is the conversion to a time-dependent wind; dynamic effects are accounted for by considering the shear-components in the same fashion as turbulence velocity components [5]. Only horizontal wind-shears are considered.

*An analysis of the lateral performance is given in [5].

Figure 1 illustrates the pertinent geometry. The aircraft's altitude (h) is given by

$$h = h_n + \delta h = R \tan \Gamma_o + \delta h \quad (6)$$

where h_n is the "nominal" altitude, i.e., the altitude of the glide-slope at the aircraft's range, R, and δh is the altitude error. The rate of change of the nominal altitude may be expressed in terms of the ground speed (or range-rate).

$$\dot{h}_n = \dot{R} \tan \Gamma_o = (U_o + u) \tan \Gamma_o \quad (7)$$

where

u = x-body axis component of perturbation in ground speed

U_o = x-body axis component of nominal airspeed

The aircraft's sink-rate is

$$\dot{h} = V \sin \gamma = (U_o + u) \sin (\Gamma_o + \Delta\gamma)$$

$$\approx (U_o + u) (\sin \Gamma_o + \cos \Gamma_o \cdot \Delta\gamma)$$

and

$$\delta\dot{h} = \dot{h} - \dot{h}_n$$

$$\approx (U_o + u) \cos \Gamma_o \cdot \Delta\gamma = (U_o + u) \cos \Gamma_o \cdot (\theta - \alpha)$$

or

$$\delta\dot{h} \approx (U_o + u) \cos \Gamma_o \cdot \theta - \frac{U_o + u}{U_o} \cos \Gamma_o \cdot w \quad (8)$$

Equation (8) is used to account for kinematic effects of shears. However, this equation is nonlinear and the product terms, $u\theta$ and uw, may not be negligible if u is a significant fraction of U_o. This is the case for the winds to be considered here. To maintain linearity and reduce the errors associated with neglecting the product terms, the "average" wind-velocity during approach was substituted for u in Equation (8); this tends to minimize the maximum error associated with assuming constant ground speed.

The wind-shears to be considered here are enumerated in Table 1. These winds are idealizations of more exact models for mean-winds. They were us d in this analysis so as to be compatible with a concurrent simulation study. We now show how these winds may be represented as time-varying disturbances; it turns out that this can be done with considerable fidelity.

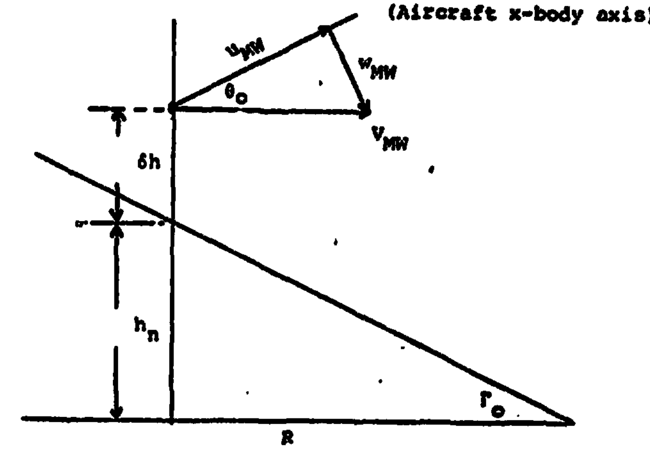

FIGURE 1. Geometry for Horizontal Wind-Shear Analysis (not to scale)

Let U_{MW} be the horizontal (along track) wind component of interest (crosswinds may be treated analogously). Given the profiles of Table 1, we may write

$$U_{MW} = U_{MW}(0) + a\,h \qquad (9)$$

where a is the change in windspeed with altitude, i.e., the shear-variation. Thus, using (7),

$$\dot{U}_{MW} = a\,\dot{h} \approx a\,\dot{h}_n = a(U_o + u)\tan\Gamma_o \qquad (10)$$

Differentiating [10] gives

$$\ddot{U}_{MW} = (a\tan\Gamma_o)\dot{u} \qquad (11)$$

Table 1

WIND-SHEARS FOR LONGITUDINAL AND LATERAL ANALYSIS

Wind	Initial Altitude	Initial Speed	Final Speed	Final Altitude
Decreasing Tailwind	152m(500 ft)	$15.45\frac{m}{s}$(30KTS)	$5.15\frac{m}{s}$(10KTS)	0
Increasing Tailwind	152m	$-5.15\frac{m}{s}$(10KTS)	$+5.15\frac{m}{s}$	0

+ Indicates tailwind or crosswind from left side.

This equation along with the dynamical equation for $\dot{u}$ allows the wind shear to be expressed in terms of other, non-input related state variables. An even simpler representation is possible. If the pilot is maintaining airspeed reasonably well, then

$$u \approx U_{MW}\cos\theta_o \qquad (12)$$

and, the state-variable representation for the mean wind disturbance is given by

$$\left.\begin{aligned} \dot{z}_1 &= \dot{U}_{MW} = z_2\ ;\ z_1(0) = U_{MW}(0) \\ \dot{z}_2 &= \ddot{U}_{MW} = (a\tan\Gamma_o\cos\theta_o)\dot{U}_{MW} \\ &= (a\tan\Gamma_o\cos\theta_o)z_2\ ;\ z_{2_{s_o}} = a\tan\Gamma_o\,(U_o + u_{MW}(0)) \end{aligned}\right\} \qquad (13)$$

where $z_{2_{s_o}}$ is the mean-wind velocity at the onset of the shear.

3.3 Results

Mean and standard deviation scores, at the decision-height (31m), are compared in Table 2. Several points are worth mentioning. First, the constant-gain no shear, zero-delay results are virtually equal to those of a corresponding steady-state analysis [5]. This is more than a check on the computer program; it shows that in the absence of shears, the approximately 1250-1300m approach distance is sufficient for the errors to reach steady-state. Second, the effect of the wind-shear is more than just a non-zero mean response. It may be seen that the standard deviation of the tracking errors and of the controls is increased. This is a result of the coupling in the model of mean-and variance-responses that arises from the dependence of the observation noises on the rms signal values and that of the motor-noise on rms control. In terms of missed approach probabilities, the increase in variance is the more significant effect. Third, the effect of time delay is, as expected, to increase mean and standard deviation of the error. The magnitude of the effect is largest for height-error with approximately a 35% increase in mean and a 10% increase in standard deviation.

Table 2

PERFORMANCE AT DECISION-HEIGHT FOR VARIOUS ANALYSIS CONDITIONS

Variable	Stea·y-State		Constant-Gains			Varying-Gains
	τ = .0	τ = .2	τ = 0	τ = 0	τ = .2	τ = 0
			No-Shear	With Shear		
$\bar{h}$ (m)	0	0	0	.16	.22	.31
σ_h (m)	1.73	1.83	1.72	2.02	2.2	2.03
$\bar{\dot{h}}$ (m/s)	0	0	0	-.01	-.016	-.05
$\sigma_{\dot{h}}$ (m/s)	.48	.50	.47	.63	.70	.63
$\bar{\theta}$ (m)	0	0	0	-.6	-.6	-.62
σ_θ (m/s)	1.24	1.29	1.23	1.27	1.35	1.26
$\bar{u}$ (m/s)	0	0	0	-.10	-.095	-.10
σ_u (m/s)	.94	.96	.96	.98	1.03	1.00
$\bar{\delta}_e$ (deg)	0	0	0	-1.44	-1.43	-1.46
σ_{δ_e} (deg)	1.38	1.5	1.39	1.75	1.94	1.82
$\bar{\delta}_N$ (deg)	0	0	0	16.3	16.2	16.5
σ_{δ_N} (deg)	8.6	8.5	8.6	11.5	11.8	11.7

The final effect illustrated in Table 2 is that resulting from allowing the gains to vary. When compared with the constant gain case, it is seen that the principal effect at the window is on the mean-response. This effect, though large percentage-wise, is virtually negligible in terms of the missed-approach probability. The differences between constant and varying gains are more p..nounced in the "time-histories" shown in Figure 2. These time-histories are curves passed through data points obtained every 50m in range. The jump-discontinuities for the varying-gain case arise from the instantaneous gain-change and

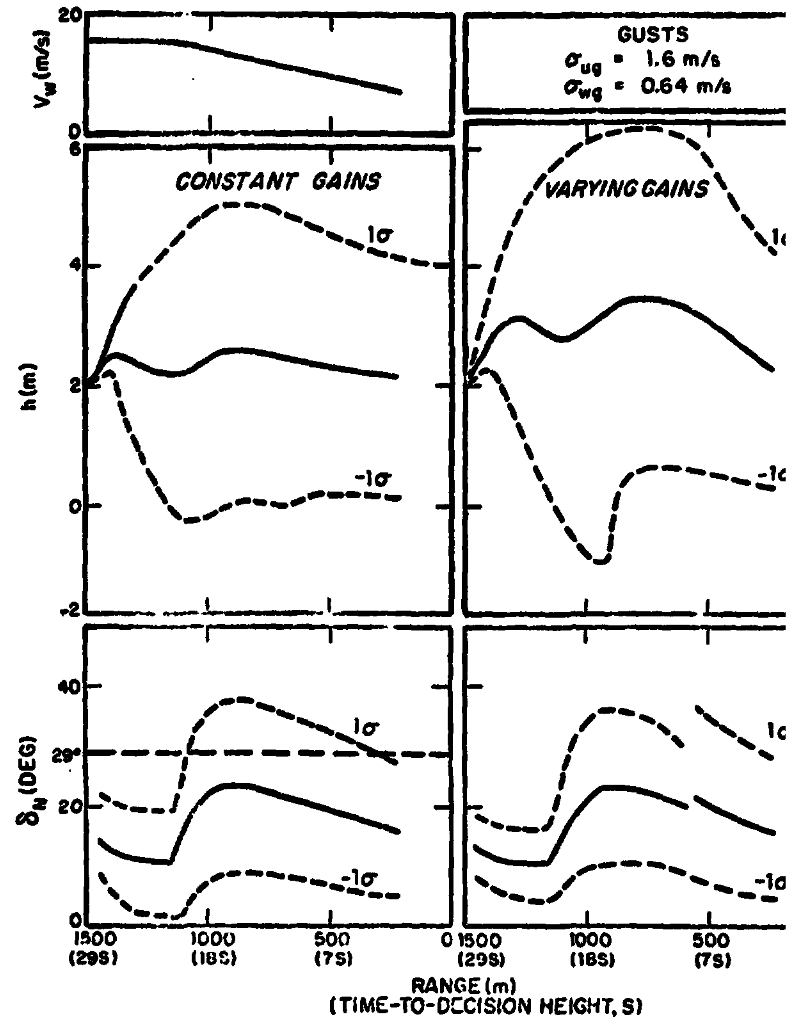

FIGURE 2. Effect of Varyi.:g Gains on Approach Trajectories (a) Height and Nozzle Response

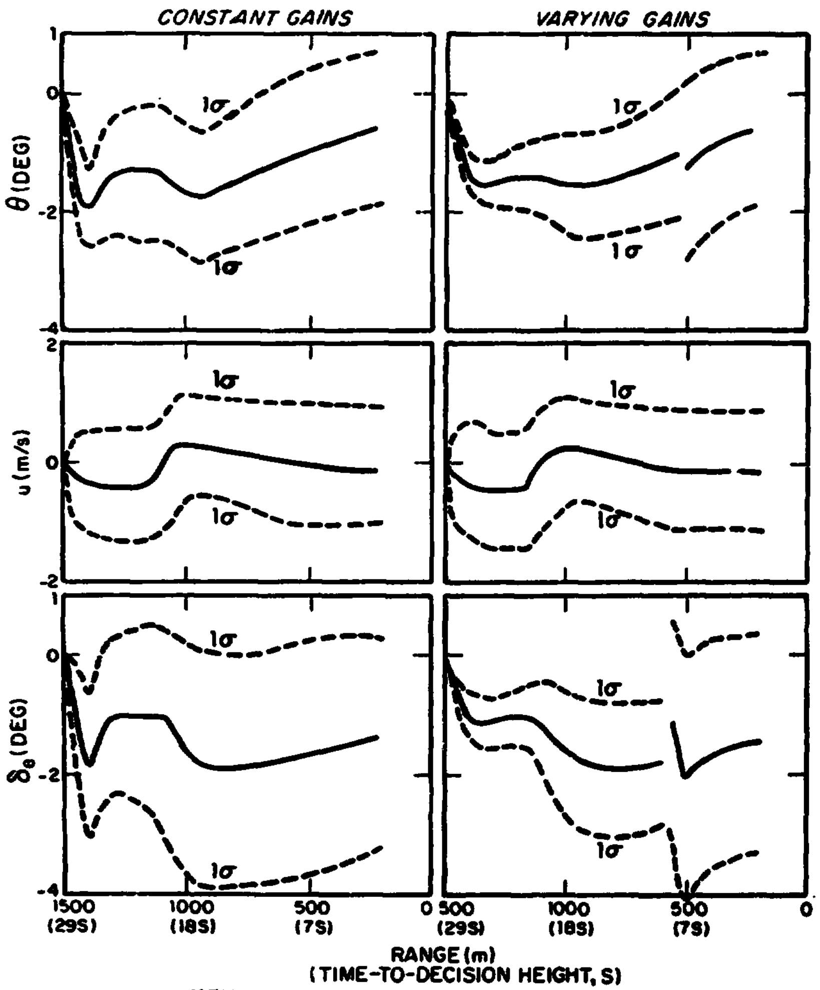

FIGURE 2. Effect of Varying Gains on Approach Trajectories
(b) Pitch, Airspeed and Elevator Response

the associated jump in control value. These "jumps" apparently decay very rapidly. Because height errors are weighted less, at more distant ranges, they are allowed to build up to a greater extent in the varying-gain case; however, as the threshold is approached the errors begin to be reduced rapidly (because of the higher weighting), so that window performance is not significantly different for the varying- and constant-gain cases (Table 2). Apart from differences in height control, the principal difference between the two-cases is in the initial transient in elevator and pitch. It seems clear that the early reduction in height errors for the constant-gain case is a result of a rapid pitch-down.

The excellent "window" performance obtained in the above analyses is somewhat misleading. As can be seen from Figure 2, the nozzle limit (29°) is less than one standard deviation from the mean for much of the approach (after the wind-velocity starts changing). Thus, a high percentage of the time the nozzle will exceed its limit. What this means is that the rate of descent capability of the aircraft, with throttle fixed, is insufficient for this wind. Further, the wind is of sufficient severity to place the entire linearized analysis in question. On the other hand, the analysis suggests that suitably scaled-down winds may be adequately controlled by nozzle and elevator inputs alone.

In an attempt to get some estimate of the control-limited performance for the decreasing tailwind, a trajectory was obtained for a case in which nozzle control and control-rate were heavily penalized in the region where excessive nozzle-control had been observed, i.e., in the 1160m < R < 575m interval. (Weightings on nozzle and nozzle-rate were multiplied by 50). To allow transient effects resulting from the initial constant wind to die out, the approach was started at 2000m. The result for height-error and nozzle-position is shown in Figure 3. It can be seen that nozzle responses to the shear variation in the heavily penalized region are virtually nil and the height errors increase accordingly. When the penalty is reduced, R < 575m, a relatively large mean-nozzle motion ensues in an attempt to reduce the mean-error. While some reduction occurs, the mean height error at the decision height is still three times the allowable Category II error. Although these results are not intended to be definitive, they do illustrate the problem posed by this wind, when the throttle is fixed.

A constant-gain trajectory for the increasing tailwind was also obtained and the results are shown in Figure 4.* The window performance for this wind is compared with that for the decreasing tailwind in Table 3. Note that the turbulence intensity and

*As can be seen the wind approximation is not as close to the idealized wind as for the previous case, but certainly good enough.

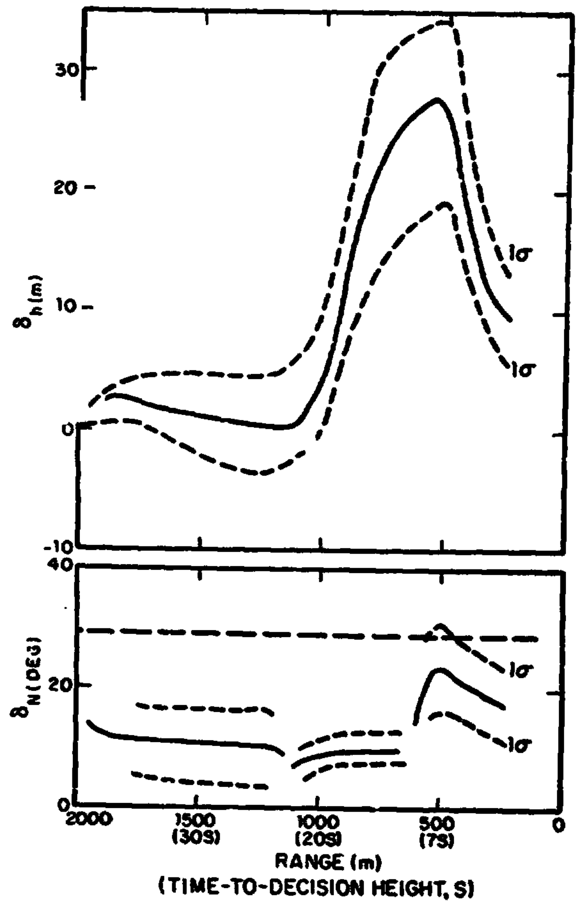

FIGURE 3. Nozzle-Limited Response for Decreasing Tailwind

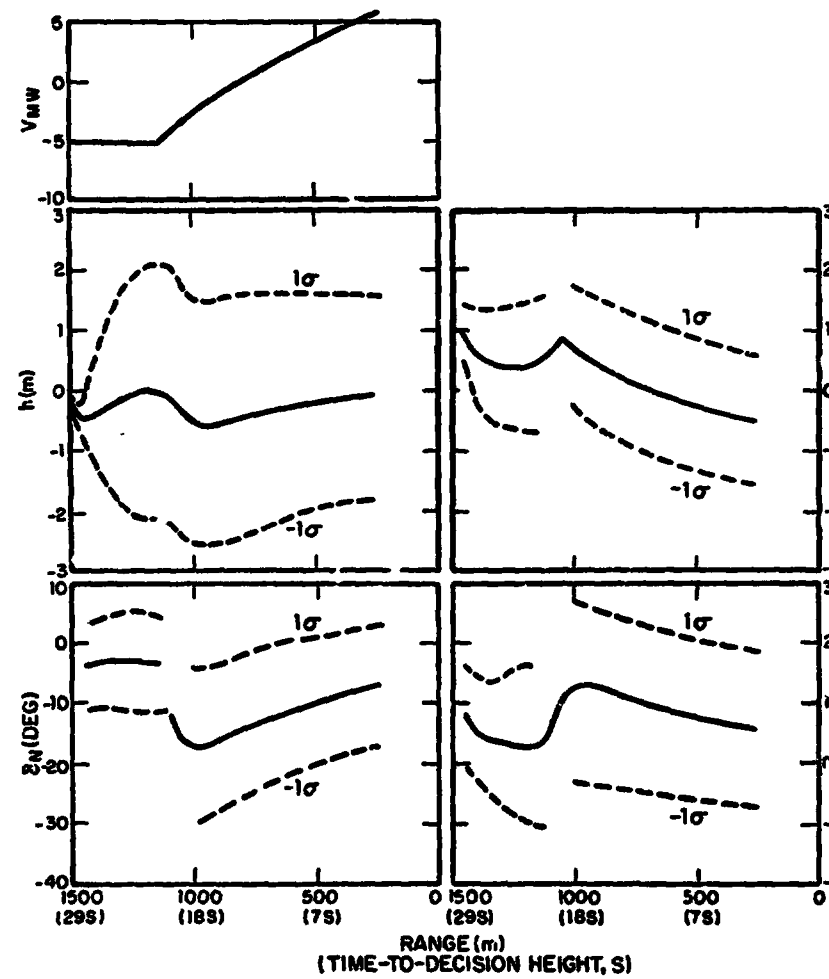

FIGURE 4. Response History for Increasing Tailwind Shear

spectrum is the same for the two cases. It may be seen that height errors are controlled more effectively for the increasing tailwind; airspeed is less-well controlled. The overall effect is a definite improvement, as could be expected. Two other points are worth noting. Referring to Table 3, we find that the standard deviation of the height and sink-rate errors for the increasing tailwind are very close to those obtained for the steady-state (no-delay) case. Thus, it appears that with the increasing tailwind (which starts out as a headwind), enough time is added to the approach to allow the "pilot" (model) to reduce the errors to values commensurate with an approach of infinite length. The second point is that the nozzle-control requirements are not so excessive (in relation to capability) as for the decreasing tailwind. Thus, one might expect these results to correspond more closely to a realistic situation.

5. CONCLUSION

Some aspects of the STOL approach in a mean-wind with shear-variation have been analyzed with the optimal control model of the human operator. Results were obtained for longitudinal control with an EADI status display. In general, the wind-shears degrade performance by producing both mean errors and increased variability in the response, with the increased variability appearing to be the major effect.

Two wind profiles were considered in the analysis of longitudinal control, a decreasing and an increasing tailwind. Relatively good performance at the window was obtained in both cases. However, for the decreasing tailwind, the results showed that with the throttle fixed, excessive nozzle-control was required for wind compensation. When the nozzle control was limited (indirectly, by penalizing control motions subsequent to shear-onset), the height errors increased significantly. The relatively good performance for the increasing tailwind was achieved with control requirements that were not so excessive and, consequently, represent a more reliable result. The better performance is undoubtedly due to the additional time available for error compensation and is, of course, to be expected.

To the extent that they were investigated, the wind-shear responses tended to confirm essentially the results of a corresponding steady-state analysis [5] (albeit that performance was worse in the wind-shear). The details of the transient responses, may be easily explained. They depend very much on the specific assumptions about initial conditions and on pilot strategy, which is not the least bit surprising. If one is interested in reproducing or predicting a particular time history (ensemble) then it is essential that conditions used in the model match those of the experiment.

With respect to future work, it appears most important to validate the results of this analysis with simulation data. Approach data is needed to pin-down details of the pilot's time-varying adaptation. Transient data for a sufficient number of runs to provide reliable statistical information would be most helpful.

Table 3

COMPARISON OF WINDOW PERFORMANCE FOR DIFFERENT TAILWINDS

Variable	Decreasing Tailwind	Increasing Tailwind
$\bar{h}$(m)	.16	-.12
σ_h(m)	2.02	1.69
$\bar{\dot{h}}$(m/s)	-.01	.006
$\sigma_{\dot{h}}$(m/s)	.63	.46
$\bar{\theta}$(deg)	-.6	-.49
σ_θ(deg)	1.27	1.13
$\bar{u}$(m/s)	-.10	-.19
σ_u(m/s)	.98	.99
$\bar{\delta}_e$(deg)	-1.44	.56
σ_{δ_e}(deg)	1.75	1.3
$\bar{\delta}_N$(deg)	16.3	-7.4
σ_{δ_N}(deg)	11.5	10.0
Time-for-Approach(s)	~29.	~43.

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