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A MODEL-BASED TECHNIQUE FOR THE DESIGN OF FLIGHT DIRECTORS*

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ABSTRACT

A new technique for designing flight directors is discussed. This technique uses the optimal-control pilot/vehicle model to determine the appropriate control strategy. The dynamics of this control strategy are then incorporated into the director control laws, thereby enabling the pilot to operate at a significantly lower workload.

A preliminary design of a control director for maintaining a STOL vehicle on the approach path in the presence of random air turbulence is evaluated. By selecting model parameters in terms of allowable path deviations and pilot workload levels, one achieves a set of director laws which allow improved system performance at reduced workload levels. The pilot acts essentially as a proportional controller with regard to the director signals, and control motions are compatible with those appropriate to status-only displays.

INTRODUCTION

Aircraft instrument panels often include a "flight director", so called, the purpose of which is to provide acceptable levels of system performance at reduced levels of pilot workload by providing the pilot with one or two display variables which combine the sensor variables in an optimal fashion. In this way, the pilot's visual scanning and attention-sharing requirements are substantially reduced. Furthermore, the pilot can obtain, from the velocity of the director indicator, derivative information (such as acceleration) not otherwise available from visual displays.

The objective of this paper is to outline a proposed new technique for determining flight director laws. This design procedure is based on application of the state-variable (or "optimal-control") model for pilot/vehicle systems (Refs. 1, 2). Application of the procedure is illustrated by the derivation of director laws for a STOL vehicle in the final approach configuration.

The proposed technique (hereinafter referred to as the "model-based" procedure) offers certain important computational advantages over alternative procedures. The model-based techniques would appear to allow the derivation of a full set of director gains with a minimum number of iterations of the design procedure. (Only a single iteration is needed for the example presented later in this paper.) Other procedures, whether they be based on analog simulation or on other forms of pilot/vehicle analysis (Ref. 3), generally require a number of iterations on the proposed director feedbacks to arrive at an acceptable design. This is especially true for situations involving multiple control variables in a single axis of control.

The model-based technique also appears to require fewer a priori assumptions relating to pilot behavior than other techniques. In order to minimize the computational effort required to carry out other design procedures, it is usually desirable to pre-specify loop closures (i.e., which sensor variables should influence which director variables). Using the state-variable procedure suggested here, one may simply assume that all sensor variables influence all control variables and proceed to compute the full matrix of director feedbacks. Such an assumption does not increase computational complexity (which depends only on the dynamical order of the system) and, as we shall show, adds only minimally to the complexity of the director design itself.

The model-based technique is not without its own judgemental requirements. The designer must postulate desired performance levels, and the available sensory variables must be specified. These considerations are common to all director design procedures, however, and do not represent a limitation peculiar to the proposed scheme.

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DIRECTOR DESIGN PHILOSOPHY

Certain constraints are imposed on the design of flight-director laws that will allow improved performance at reduced levels of pilot workload. The director variables must be composed of signals that can be generated by available aircraft measurement devices. These signals are commonly combined in such a way as to make the combined director/vehicle dynamics approximate a K/s-like behavior so that the need for pilot lead is minimized. Considerations of pilot acceptance also suggest that required control inputs and resultant vehicle motions be similar to those that are appropriate to flight with conventional displays. In addition, the director signal should provide the pilot with a good indication of instantaneous flight-path and attitude errors so that frequent reference to status displays is not required.

If the director is a control director (i.e., if it provides the pilot with an explicit indication of the desired control response), a director signal must be generated for each control variable. An ideal design should require little or no pilot coupling so that a given director variable commands a control response along a single dimension.

The preliminary design procedure outlined below allows one to approach many of the above design goals in a relatively straightforward manner. The following design steps have been followed in deriving the control-director for the numerical example presented in this page.

1. Define the control situation in terms of system dynamics, input characteristics, sensory information, performance requirements, and pilot parameters.

2. Use the pilot/vehicle model to predict the pilot-generated feedbacks between each display variable and each control variable.

3. Approximate each of the transfers by a first- or second-order filter. (This approximation simplifies both analytical evaluation and implementation of the resulting director laws.)

4. Derive the commanded control signal by summing the outputs of the transfers between all sensor variables and the control variable appropriate to the director. The director signal is thus expressed as

$$D_i(s) = \sum_j T_{i_j}(s) \cdot Y_j(s)$$

where D_i is the director signal appropriate to the i_{th} control variable, Y_j is the j_{th} sensor variable, and T_{ij} is the approximate describing function between the j_{th} sensor variable and the i_{th} control variable.

5. Evaluate the proposed director laws using the pilot/vehicle model. If an inappropriate "mix" of flight-path errors, attitude errors, and control motions is predicted, repeat the design with a revised set of cost weighting coefficients. If performance is still inadequate, additional sensory variables may be have to be considered.

In essence, the flight director laws are designed to perform the equalization and cross-coupling that the pilot would otherwise have to do. With the director in the system, the pilot's task is basically that of generating a control response proportional to the deflection of the corresponding director indicator. Thus, cross-coupling should be at a minimum, and the pilot's response strategy should be approximately that of a pure gain at low and mid frequencies.

If the sensor variables and performance requirements assumed for the director design are the same as would apply to the control task with a more conventional display panel, the characteristics of control and vehicle motions should not be appreciably changed by the use of the director. Nevertheless, the consequent reduction of pilot-related "noise" associated with scanning, attention-sharing, and visual resolution limitations should allow a substantial improvement in performance and/or a reduction in pilot workload. If additional sensory information (such as linear or rotational accelerations) is used in generating the director signal, further improvement may be expected.

NUMERICAL EXAMPLE

The following numerical example is presented to demonstrate the model-based design procedure outlined above. Control-director laws are derived for longitudinal-axis control of an augmentor-wing jet STOL aircraft (C8-M) in a steep (7.5 deg) approach-to-landing configuration. Longitudinal and vertical random-wind disturbances are considered, and linearized perturbation equations are used to describe aircraft dynamics. Two control variables are considered: the elevator control, and the "nozzle" control which regulates the direction of the thrust vector.

The director laws derived below are intended only as a preliminary flight director design — not one that would necessarily be implemented without modification. For example, a realistic design effort would involve consideration of additional factors such as wind-shears, beam capture, and random fluctuations of the signal which generates the desired glide slope ("beam noise"). In addition, the director laws would have to prohibit the possibility of "stand-off" errors in which a steady-state error in one variable compensates for a steady-state error in another variable to yield a zero reading on the director. Nevertheless, the following example does illustrate the essence of the design procedure, and we consider the predicted improvements in performance and workload to be representative of the benefits that would be obtained in practice.

Definition of the Control Situation

The control situation used in this example has been described in considerable detail in Reference 4 and to a lesser extent in a companion paper (Ref. 5). Accordingly, only those aspects of the situation critical to an understanding for the director design procedure will be elaborated upon here. The reader is directed to the above references for a description of the vehicle dynamics and wind-gust characteristics assumed in this example.

No description of the pilot/vehicle model is given here, as this model has been well documented in the literature (Refs. 1, 2). The rationale for selecting model parameters will, however, be discussed.

The sensory information available to the flight director was assumed to be the same as the flight-control information available to the pilot through his status displays; namely, (a) height error, (b) sink-rate error, (c) pitch deviation from trim, (d) pitch rate, and (e) airspeed error. (Lateral-directional variables are not considered in this example.)

Performance requirements were specified in terms of a (scalar) quadratic cost functional that combined deviations associated with flight-path, attitude, and control variables. Weighting coefficients for this cost functional were selected on the basis of maximum allowable deviations (or "limits") for the various problem variables. A unit amount of "cost" was associated with a given variable when the magnitude of the "error" (i.e., deviation from trim) was equal to the nominal limit. Thus, the weighting coefficient for each variable was computed simply as the inverse of the square of the corresponding limit. Height-error and airspeed limits were based on Category II "window" specifications; control and control-rate limits were determined largely from physical considerations, and the remaining limits were based on assumed pilot preferences.

The limits assumed for this analysis and the resulting weighting coefficients are shown in Table 1.

Table 1

"LIMITS AND COST FUNCTIONAL WEIGHTINGS"

Variable	"Limit"	Weighting
h	3.7 (m)	0.073
$\dot{h}$	1.1 (m/s)	0.83
θ	6.0 (deg)	0.028
q	(none specified)	0.0
u_i	2.6 (m/s)	0.15
δ_e	9.0 (deg)	0.012
δ_N	29. (deg)	0.0012
$\dot{\delta}_e$	50. (deg/s)	0.0004
$\dot{\delta}_N$	100. (deg/s)	0.0001

On the basis of previous analysis of manual control behavior (Refs. 1, 2), pilot time delay was assumed to be 0.2 seconds. Pilot-related "noise" levels, on the other hand, were set at levels considerably greater than those found in the laboratory. The rationale for choosing noise levels is as follows.

The selection of model noise/signal ratios for flight director design depends on whether one views the benefit of the director as primarily the reduction of system errors or the reduction of pilot workload.* If the pilot is expected to maintain a high level of workload so that he can minimize errors, low noise/signal ratios appropriate to maximal effort should be used in the analysis. On the other hand, if the director is intended mainly to allow the pilot to maintain performance with reduced workload, then the director should be optimized for substantially larger noise/signal ratios.

*The basis for relating noise parameters of the model to attentional workload is discussed in Refs. 6 and 7.

Although a director designed for a low-noise situation will allow better performance under conditions of maximal effort, the alternative design will be less sensitive to pilot noise and should thus be more "forgiving" of non-optimal pilot behavior. Accordingly, the director laws designed and evaluated in this study have been obtained by computing predicted pilot describing functions for a high-noise situation.

Specifically, levels of -10 dB were used for both motor and observation noise/signal ratios (as opposed to levels of -20 dB for observation noise and -25 dB for motor noise typically derived from laboratory tracking data). Attention-sharing was not specifically considered – the large noise/signal ratios already took this factor into account – and display-related thresholds and resolution limitations were ignored.

Derivation of Director Laws

Pilot describing functions were obtained from a steady-state analysis of pilot/vehicle performance. Wind gust intensities corresponded to the "1-percent" wind condition. That is, gust intensities greater than these levels would be encountered in practice only 1% of the time. Thus, a "worst-case" analysis was performed.

Predicted pilot describing functions (magnitudes only) relating the elevator and nozzle controls to each of the five display variables are shown in Figures 1 and 2.* Since the frequency-dependencies of the five transfers associated with a given control variable were nearly identical, only two shaping filters were required to generate the director laws.

Specifically, each of the predicted pilot transfers was approximated by the transfer function of a second-order, critically-damped low-pass filter. The critical frequencies of all responses corresponding to a given control variable were made identical. Thus, each of the two director signals was represented as follows:

$$D_i(s) = \sum_j K_{i_j} \cdot \left[\frac{1}{1+s/\omega_i}\right]^2 \cdot y_j(s)$$

where ω_i is the critical frequency of the filter associated with the i_{th} control variable and K_{ij} is asymptotic low-frequency behavior of the approximate transfer function relating the i_{th} control variable to the j_{th} sensory input.

*For the purposes of this design exercise, velocity variables (pitch rate and sink rate error) were considered to be sensory variables distinct from the corresponding position variables. Hence, five pilot describing functions were computed for each control variable.

Approximations to the predicted internal describing functions were obtained by visual inspection. The resulting director parameters are shown in Table 2. The units of the low-frequency gains are in terms of relevant display and control variables. For example, the gain associated with the contribution of height information to the elevator director has units of degrees (of control surface deflection) per meter (of height error). Critical frequencies are in radians/second.

Table 2

PARAMETERS FOR MODEL-BASED LONGITUDINAL DIRECTOR LAWS

Director	Sensory Variable	Critical Frequency	Low-Frequency Gain
Elevator	Height	5.0	0.25
	Sink Rate		1.8
	Pitch		0.9
	Pitch Rate		0.8
	Airspeed		0.5
Nozzle	Height	3.5	1.1
	Sink Rate		6.3
	Pitch		0.8
	Pitch Rate		1.0
	Airspeed		6.3

The ability to approximate each set of five pilot describing functions with a single shaping filter is an encouraging result, for it shows that the complexity of the problem is negligibly affected by the number of display-to-control closures that are considered. That is, two shaping filters are needed whether there is one closure per control variable or whether there are five. Additional closures merely add additional gain coefficients which contribute minimally to the design complexity of the director. Furthermore, these additional coefficients do not increase the computational effort involved in analyzing the proposed design with the state-variable model.

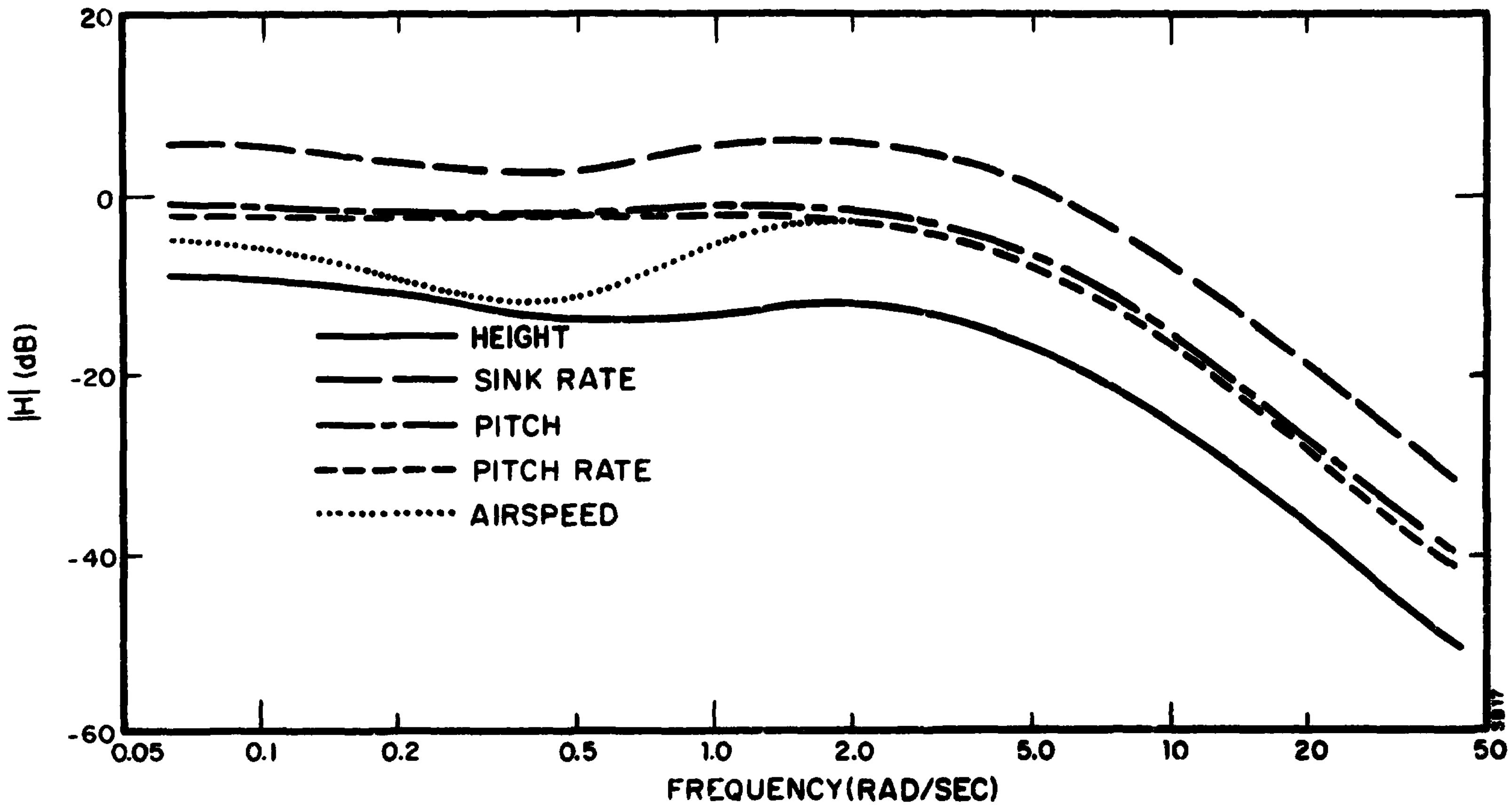

FIGURE 1. Magnitudes of Internal Pilot Describing Functions for Elevator Control

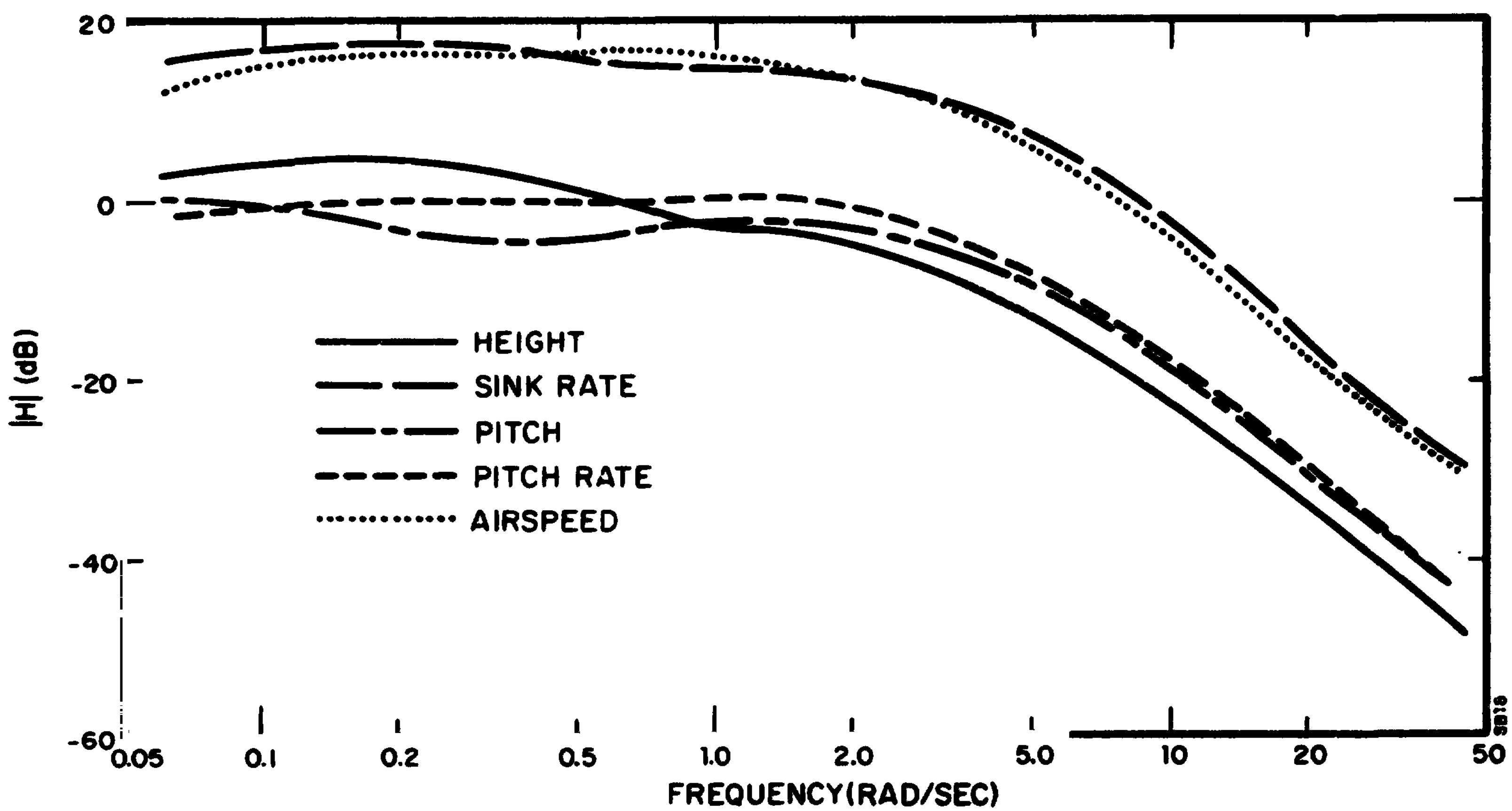

FIGURE 2. Magnitudes of Internal Pilot Describing Functions for Nozzle Control

Further experience with the proposed technique is needed to determine whether such simplifications can be made in general. If such is found to be the case, then we have demonstrated a very powerful technique for designing a control director of minimal complexity.

Evaluation of the Director Laws

For the purpose of evaluating the proposed control-director laws, pilot-related model parameters were selected to correspond to a high level of pilot effort. Parameters not related to pilot randomness were set to the same values used in the design procedure. The motor noise/signal ratio was set to approximately -25 dB, and, in order to perform a workload analysis (Refs. 6, 7), the observation noise/signal ratio was varied from a minimum of -20 dB to a maximum of about -10 dB.

Performance. — Predicted rms performance scores for the 1%-wind condition and an observation noise/signal ratio of -20 dB are shown in Table 3. Also shown for comparison are the scores predicted for the status displays without a flight director and the scores associated with an idealized display condition which ignores most of the display-related limitations (Refs. 4, 5).

The performance variable most effected by display parameters is the rms height error. The score predicted with the flight director is about 26% less than the score predicted for the status display. (The idealized display yields about a 35% reduction with respect to the status display.) A similar reduction is predicted for the sink rate error score. A reduction of about 10% is predicted for rms stick and stick rate. Other performance scores are virtually unchanged. Except for improved flight-path performance, then, vehicle motions and control responses are essentially the same with and without the flight director.

Workload. — In order to assess the degree to which workload can be reduced by the use of the flight director, we examine the relationship between the probability of a "missed approach" and "attention". A missed approach is defined as the situation in which either height or airspeed error exceeds its respective "limit" of 3.7 meters or 2.6 meters/second. Attention is related inversely to the observation noise/signal ratio, with a relative attention of unity associated with a ratio of -20 dB.

Table 3

COMPARISON OF PREDICTED RMS PERFORMANCE WITH
VARIOUS DISPLAY CONFIGURATIONS

(1%-wind, P_o = - 20 dB)

Variable	Display Condition: Without Flight Director — Status	Without Flight Director — Idealized	With Flight Director
σ_h (m)	2.3	1.5	1.7
$\sigma_{\dot{h}}$ (m/s)	.68	.55	.55
σ_θ (deg)	1.8	1.8	1.8
σ_q (deg/s)	1.2	1.2	1.1
σ_u (m/s)	1.3	1.3	1.3
σ_{δ_e} (deg)	2.1	2.0	1.9
$\sigma_{\dot{\delta}_e}$ (deg/s)	7.4	7.0	6.6
σ_{δ_N} (deg)	12.	12.	12.
$\sigma_{\dot{\delta}_N}$ (deg/s)	21.	21.	21.

The relation between predicted performance and attention is shown for the 1%-wind condition in Figure 3a. Curves for both the status and director displays are shown for comparison. For the 1%-wind condition performance is still poor for the director display, but it is appreciably better than for the status display configuration. In particular, the flight director reduces significantly the sensitivity of performance to observation noise (both display-related and human related) and, therefore, shows relatively greater improvement at lower levels of pilot attention.

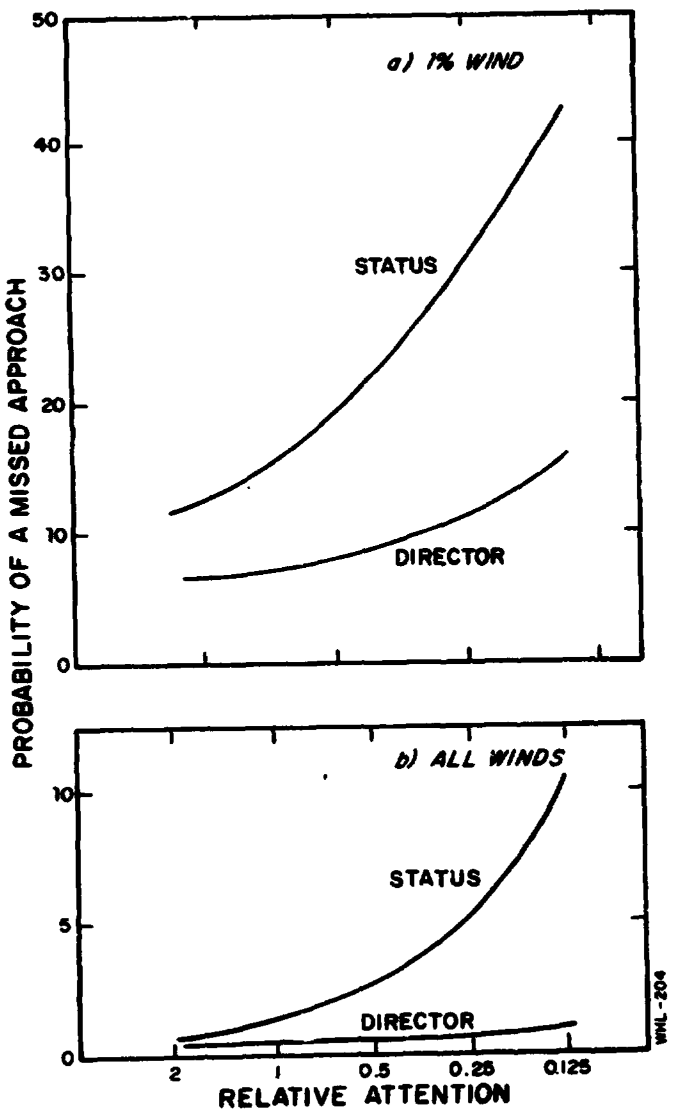

FIGURE 3. Relation Between Predicted Performance and Attention

In order to provide a more meaningful comparison of the workload/performance relationships for the two display configurations, a probability-weighting procedure was employed to derive a set of curves corresponding to "average" gust conditions (Refs. 4, 5). The value of the flight director is now even more apparent. The predicted workload requirements are substantially lessened even for relatively stiff performance demands. For example, if we require a 99-percent probability of a successful approach, a relative pilot attention of slightly greater than unity is required when no director is provided. With the proposed director, however, predicted attention requirements are reduced by about a factor of 10. Conversely, performance is improved for a pilot operating at a constant level of attention. For a relative attention of 0.25, the predicted probability of a missed approach is reduced from about 5 percent for the status display to around .6 percent for the "model-based" director.

Predicted Pilot Describing Function. — One of the design goals set forth earlier was that the flight director should allow the pilot to adopt a control strategy that resembles a simple gain at low and mid frequencies. We expected that the design procedure adopted in this study would meet this requirement by allowing the director laws to perform the required equalization. It was also anticipated that cross-coupling in the pilot's response strategy would be unnecessary with a properly designed set of flight directors.

Inasmuch as the model for the pilot is relatively "free form", pilot transfers will in general be predicted between all display and all control variables. Thus, for the control situation investigated here, there are two sets of predicted pilot describing functions to consider: the "direct" transfers which relate each control response to the corresponding director command, and the "cross" transfers which relate control responses to commands on non-associated directors. In cases where pilot cross-coupling is unimportant, the magnitudes of the predicted cross transfers should be numerically small.

The predicted direct transfers are shown in Figure 4. As expected, these transfers approximate a pure gain at frequencies up to about 4 rad/sec (which is beyond gain-crossover for flight-path and attitude control). The high-frequency peaks in the amplitude ratios are typical of actual pilot response behavior obtained in K/s tracking situations.

Predicted cross transfers are shown in Figure 5. The frequency-dependency of the phase-shift indicates that both describing functions are non-minimum-phase.

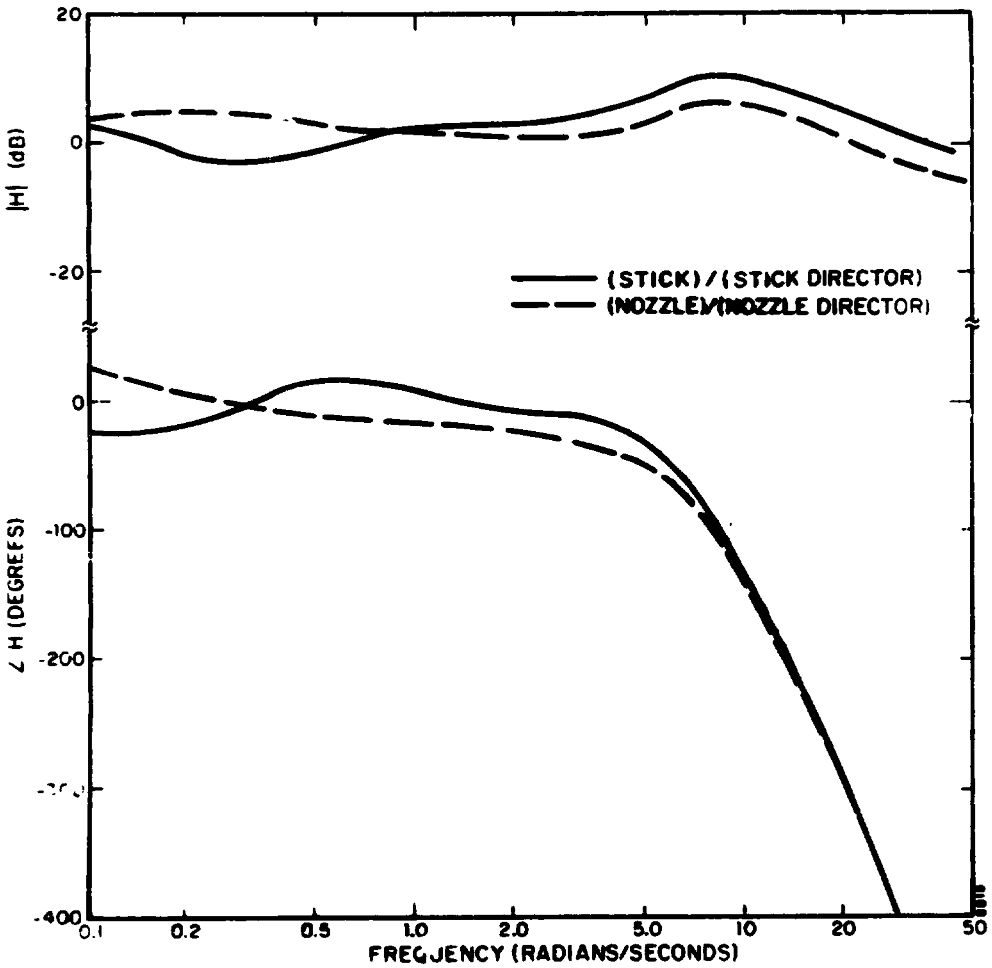

FIGURE 4. Predicted "Direct" Pilot Transfers

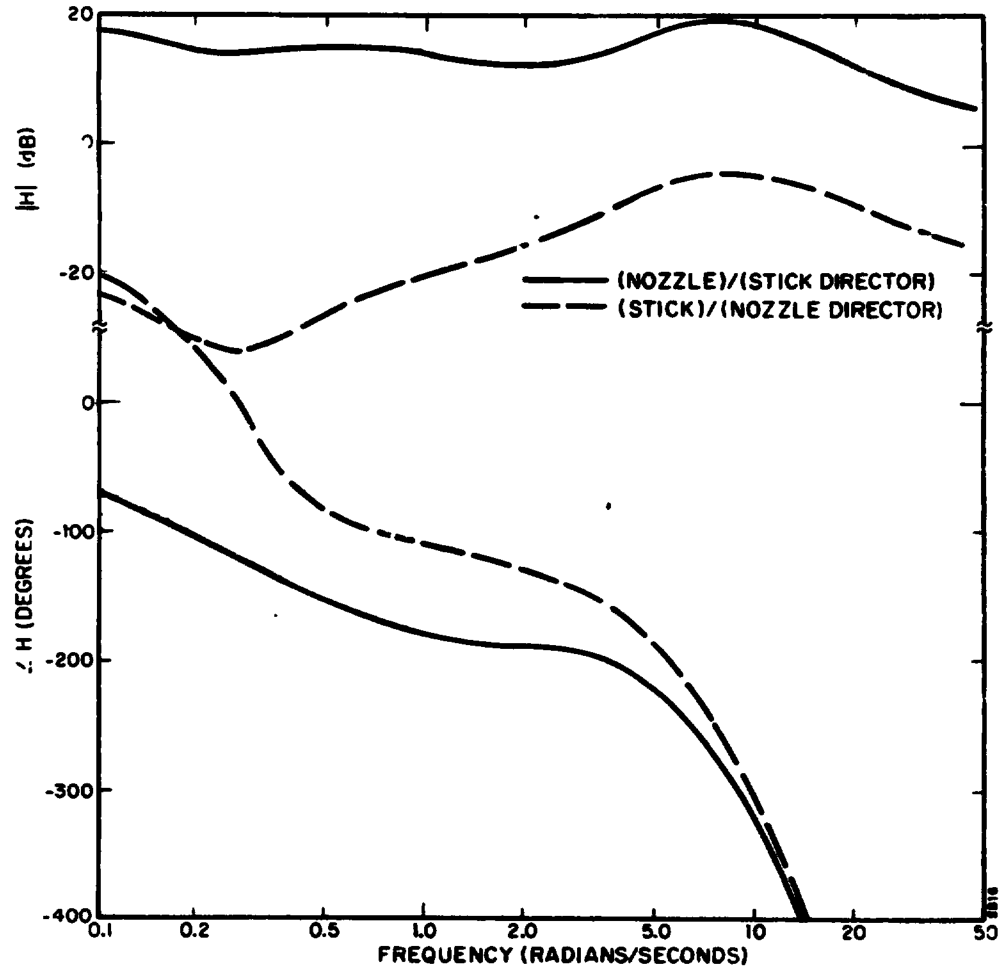

FIGURE 5. Predicted "Cross" Pilot Transfers

In order to determine whether or not the magnitude of the cross transfers are small enough to be neglected, we must compare the open-loop describing functions for the direct and cross paths. (The open-loop transfer is defined as the cascade combination of a predicted pilot describing function and the corresponding vehicle transfer function.) Such a comparison (not shown here) reveals that the magnitudes of the cross control paths are not substantially less than the magnitudes of the direct paths at all frequencies. Thus, we cannot claim that the predicted pilot cross couplings are numerically small.

A true test of the importance of cross-coupling would be to determine the levels of performance and workload that would be obtained if cross coupling were prohibited. There is no simple way to make this test at present, however, because current implementation of the pilot/vehicle model does not allow for such a constraint on the predicted control strategy.

SUMMARY

An approach to designing flight director laws based on the "optimal-control model" of the human operator was suggested. Director laws for longitudinal control of a STOL vehicle were developed using this approach. Analysis of system performance with status displays and with the proposed director display led to the prediction that the director would provide improved system performance at reduced workload levels. Thus, the proposed design technique achieved its major objectives. On the other hand, the results did not substantiate the belief that the need for control cross-coupling would be reduced by this design procedure. Further work is necessary to evaluate this aspect of the design.

It should be re-emphasized that the illustrative example presented in this paper resulted in only a preliminary design of director laws and an analytic (not experimental) evaluation thereof. A number of factors such as steady-state winds, sensor noise, and stand-off errors were not considered, and design compromises that are perhaps inevitable in practice were unnecessary here. Nevertheless, the author believes that the results presented here are highly encouraging and warrant both further development and experimental evaluation of the design technique proposed in this paper.

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