Closed-Loop Pilot Vehicle Analysis of the Approach and Landing Task

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Optimal-control-theoretic modeling and frequency-domain analysis is the methodology proposed to analytically evaluate the handling qualities of higher-order manually controlled dynamic systems. Fundamental to the methodology is evaluating the interplay between pilot workload and closed-loop pilot/vehicle performance and stability robustness. The model-based metric for pilot workload is the required pilot phase compensation. Pilot/vehicle performance and loop stability is then evaluated using frequency-domain techniques. When these techniques were applied to the flight-test data for thirty-two highly-augmented fighter configurations, strong correlation was obtained between the analytical and experimental results.

Nomenclature

A, A_v, A_k, A_c = plant matrices
b, b_v, b_k = control vectors
C, C_v, C_k = output matrices
d, d_v, d_k = disturbance vectors
e, e_c = process noise vectors
$E\{(\cdot)\}$ = expectation operator
g = weighting on pilot input rate
$H(s)$ = pilot model transfer matrix
I = identity matrix
J = pilot model objective function
K = algebraic Riccati solution matrix
l_e = pilot model state gain matrix
$P_{(\cdot)}$ = effective pilot model describing function for response $(\cdot)$
q = pitch rate, weighting on flight path error
r = weighting on pilot input
s = dependent variable for Laplace transform
SP = sensitivity parameter
u = input, perturbed forward speed
u_p = pilot stick input
U_o = trim forward velocity
V = covariance of observation noise, v
w = perturbed plunge velocity, plant process noise
x_v, x_c, x_k = state vectors
y_p = pilot model observation vector
α = angle of attack
γ = vehicle flight path
γ_c = flight path commanded
γ_e = flight path error, $\gamma_c - \gamma$
δ_e = elevator deflection
$\zeta_{(\cdot)}$ = damping ratio of mode$(\cdot)$
θ = vehicle pitch attitude
θ_c = pitch attitude commanded
$\sigma_{(\cdot)}$ = rms of $(\cdot)$
Σ_1 = steady state estimation error covariance
τ = pilot model time delay
τ_n = pilot model neuromotor time constant
τ_1, τ_2 = flight control system time constants
$\tau_{\theta 2}$ = pitch numerator time constant
$\omega(\cdot)$ = undamped natural frequency of mode $(\cdot)$
$\angle(\cdot)$ = phase angle of transfer function $(\cdot)$
$|(\cdot)|$ = magnitude of $(\cdot)$

Received Aug. 12, 1985; presented as Paper 85-1851 at the AIAA Guidance, Navigation, and Control Conference, Snowmass, CO, Aug. 19-21, 1985; revision received May 29, 1986.

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Introduction

ONE important tool in handling-qualities research is the application of closed-loop analysis techniques to expose undesirable dynamic characteristics in the combined pilot and vehicle system. The pilot has been frequently characterized by servo-analytic techniques in the frequency domain. One advantage is that the results are in a form very useful to, and understood by, the flight control designer. Much of this work was based on a quasi-linear pilot modeling technique, developed and reported by McRuer et al.[1]

A significant contribution obtained from a similar technique was furnished in 1970 by Neal and Smith.[2] In this work, Neal and Smith were able to correlate Cooper-Harper[3] subjective pilot ratings with frequency-domain characteristics of the pilot/vehicle system, as modeled, for a precision pitch-attitude-tracking task. A single-loop, servo-analytic pilot modeling approach was used in this work.

However, the frequency-domain pilot models discussed thus far have been somewhat limited to single-input, single-output systems. Multiloop models have been implemented by using sequential loop closure techniques, with some limited success. The difficulty in the multiloop case arises in that assumptions are required as to the pilot/vehicle system's loop structure and the proper form of the pilot's loop compensation. There are also several difficulties in characterizing task constraints in the frequency domain alone (i.e., required bandwidth).

In the early 1970s, Kleinman, Baron, and Levison[4] put forth a human operator modeling technique based on a time-domain, optimal-control approach. This approach has the potential to be very adaptable for more complex, multiloop situations or tasks. However, much of the research based on this pilot modeling technique has been focused on attempts to predict human operator and vehicle time responses, or, more specifically, statistical performance. Usually, such statistical information is not the most useful to the flight control designer.

Recently, Bacon and Schmidt[5] presented an integrated optimal-control, frequency-domain (OC/FD) approach for pilot/vehicle analysis of the precision pitch-attitude control task. When applied to the flight test results of Neal and Smith, the optimal-control approach was shown not only to agree

Table 1 LAHOS report control system dynamics

First order lag	$\dfrac{1}{\tau_2 s+1}$
First order lead lag	$\dfrac{\tau_1 s+1}{\tau_2 s+1}$
Second order lag $\zeta_3=0.7$	$\dfrac{1}{\dfrac{s^2}{\omega_3^2}+2\dfrac{\zeta_3}{\omega_3}s+1}$
Fourth order lag, Butterworth filter to model digital lag $\zeta_3=0.93$, $\zeta_4=0.38$, $\omega_3=\omega_4=16(\text{rad/s})$	$\dfrac{1}{\left(\dfrac{s^2}{\omega_3^2}+2\dfrac{\zeta_3}{\omega_3}s+1\right)\left(\dfrac{s^2}{\omega_4^2}+2\dfrac{\zeta_4}{\omega_4}s+1\right)}$

extremely well with their original results, but it also yielded additional information on achievable closed-loop bandwidth. This methodology also allows a quantitative task definition in the time domain. The pitch-attitude-tracking task was still modeled as a single-input, single-output, closed-loop task, as shown in Fig. 1, but the optimal-control approach was used to obtain reasonable analytic estimates of the pilot's adaptable dynamics, $P(s)$, in the pilot/vehicle systems.

The research described herein, and in considerable detail in Anderson,[6] presents an extension of the methodology of Bacon and Schmidt to the more complex approach, flare, and landing task. It is usually understood that this task is multiloop in nature, and the difficulty has been in the estimation of the appropriate pilot loop closures and dynamic compensation. In addition, developing a single model-based metric correlating with workload has been difficult, given multiple pilot loop closures instead of a single, combined pilot/vehicle control loop. The fundamental approach here is to use the time-domain, optimal-control method to estimate the pilot loop closures, and then to perform a frequency-domain analysis which yields a single dynamically-equivalent loop. Finally, the equivalent single loop representation is evaluated to extract pertinent vehicle handling quality information. The vehicle configurations in consideration here are those initially reported by R.E. Smith[7] in the LAHOS (Landing and Approach of Higher Order Systems) study. It is again emphasized that what is sought in this analysis is an analytical methodology that will expose unacceptable vehicle dynamics in a piloted task and will at the same time aid in identifying and understanding desired vehicle characteristics.

The Experimental Data Base

The LAHOS report summarizes flight tests that used the USAF/Calspan NT-33A variable stability aircraft to study highly augmented fighter aircraft in the landing flight phases under VFR conditions. Several of the configurations were flown with additional control system dynamics described in Table 1. These additional dynamics were used to represent the possible control system dynamics that are frequently present in highly-augmented aircraft. A summary of the thirty-two configurations selected for study herein is included in Table 2.

The airframe longitudinal dynamics for the configurations are represented by the standard form

$$\dot{x}_v(t)=A_v x_v(t)+b_v u(t) \tag{1}$$

where the state vector is defined by $x_v^T=[u,w,\theta,q]$, and the control $u(t)$ is the elevator deflection $\delta_e(t)$. Using the approximations

$$\gamma(t)=\theta(t)-(1/U_o)w(t)$$
$$\dot{\gamma}(t)=[n_z(t)-1]g/U_o$$

the vehicle responses of interest may be written

$$y(t)=C_v x_v(t)+d_v u(t) \tag{2}$$

where

$$y^T=[\theta,q,\gamma,n_z].$$

As previously mentioned, the different configurations flown for the LAHOS study include a variety of additional control system dynamics. Each of these sets of additional dynamics can be represented by

$$\dot{x}_k(t)=A_k x_k(t)+b_k u_p(t)$$
$$u(t)=C_k x_k(t)+d_k u_p(t) \tag{3}$$

where $u_p(t)$ is the stick force applied by the pilot.

Critical Task Modeling

Clearly, for aircraft without direct-lift devices, the ability to control pitch-attitude is necessary in any longitudinal task. But to what extent the pilot has to precisely control attitude such that he can effectively control flight path, for example, is an interesting question to be considered. We will attempt to shed some light on this question by performing an attitude analysis proposed by Bacon and Schmidt. Since that analysis procedure is described in Ref. (5), how it is performed will not be repeated here. However, an additional "critical task analysis" will be developed, and it is intended to give additional information on the vehicle characteristics deemed important in the landing task.

In the approach, flare, and landing task, both altitude and vertical velocity are clearly of critical interest to the pilot. These parameters are both related to the vehicle flight path, which is controllable by the pilot through elevator position commands (in the conventional frontside approach). It is hypothesized, therefore, that the ability to precisely control flight-path angle is a necessary condition to obtain good pilot ratings for that particular vehicle dynamic configuration in the *approach, flare, and landing task.*

The ability to precisely control flight-path angle, in an analytical sense, is equivalent to the ability to minimize the deviation of flight-path angle from a desired path. A compatible pilot objective, in such a case, may then be stated in the form of a quadratic cost function, as used in the optimal-control modeling approach. An appropriate objective function is then

$$J(u_p)=E\left\{\lim_{T\to\infty}\frac{1}{T}\int_0^T\left(q\gamma_e^2+ru_p^2+g\dot{u}_p^2\right)\mathrm{d}t\right\} \tag{4}$$

where γ_e = flight path error, and u_p = pilot's control input.

With the pilot model objective defined, attention must be focused on what observations are available to the pilot in the landing task. It was noted that pitch-attitude information is very important in any longitudinal task. For a VFR task, as in the experiment, vehicle responses available to or sensed by the pilot are pitch attitude, pitch rate, and plunge acceleration. Also, vertical speed, or sink rate, is observable. Due to the kinematic relationship among these variables, it may reasonably be assumed that the pilot could close control loops based on θ and $\dot{\theta}$ as well as γ and $\dot{\gamma}$ information. Finally, deviation from some desired flight path would be important, and "sensed" somehow, at least internally by the pilot himself.

To complete the critical task definition, some appropriate characterization of the frequency content of the flight-path to be tracked, or $\gamma_c(t)$, is necessary. Note that with regard to the precision tracking performance of the closed-loop pilot/vehicle system, it makes little difference whether the desired flight path is internally generated by the pilot or is some external or exogenous command like a flight director, for example. The important consideration in meeting the analysis objectives is

Table 2 LAHOS Configuration summary

Config. no.	Pilot ratings	Aircraft dynamics	Additional dynamics		
		ω_{sp},rad/s/ζ_{sp}	τ_1,s	τ_2,s	ω_3,rad/s
1-C	4,4		0.2	0.1	—
1-1	4	1/0.74	—	—	—
1-3	9,10		—	0.25	—
1-6	5		—	—	16
2-A	4,6		0.4	0.1	—
2-C	1.5,1.5,3,4		0.2	0.1	—
2-1	2		—	—	—
2-2	4,4.5		—	0.1	—
2-3	6	2.3/0.57	—	0.25	—
2-6	5		—	—	16
2-7	6,7		—	—	12
2-9	10		—	—	6
2-11	8		—	—	16(4th)
3-C	2,5		0.2	0.1	—
3-1	4,5,7		—	—	—
3-2	7	2.2/0.25	—	0.1	—
3-3	10		—	0.25	—
3-6	6,7		—	—	16
4-C	3,3		0.2	0.1	—
4-1	2		—	—	—
4-4	6,7	2/1.06	—	0.5	—
4-6	4		—	—	16
4-7	3		—	—	12
4-10	9		—	—	4
5-1	5,7		—	—	—
5-3	4.5,6,6,8		—	0.25	—
5-4	6	3.9/0.54	—	0.5	—
5-5	7		—	1	—
5-6	6		—	—	16
5-11	7		—	—	16(4th)
6-1	10		$\frac{16(.5s+1)(.43s+1)}{(.2s+1)(1.1s+1)(s^2+2(4)(.7)s+16)}$		
		1.9/0.65			
6-2	2		$\frac{(.5s+1)(.43s+1)(.06s+1)}{(.2s+1)(1.1s+1)(.1s+1)}$		

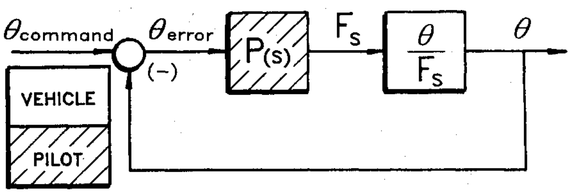

Fig. 1 Neal-Smith/Bacon-Schmidt pitch attitude tracking task.

not to actually model a desired glide path, but to adequately and consistently represent command signal frequency content that is reasonable for the landing task.

With this in mind, a pre-filter driven by "white" noise is used to generate a random pitch-attitude signal, with frequency content similar to that in the original discrete instrument pitch-tracking task used by Neal and Smith. This signal is not considered for display to the pilot, but is used to generate a representative command flight path signal using the vehicle's γ/θ response relationship.

$$\frac{\gamma_c(s)}{\theta_c(s)}=\frac{1}{\tau_{\theta_2}s+1} \tag{5}$$

A value of $1/\tau_{\theta 2}=0.5\ \mathrm{s}^{-1}$ was chosen here. The command dynamics are then expressible as

$$\begin{bmatrix}\dot\theta_c\\ \ddot\theta_c\\ \dot\gamma_c\end{bmatrix}=\begin{bmatrix}0 & 1 & 0\\ -0.25 & -0.5 & 0\\ 0.5 & 0 & -0.5\end{bmatrix}\begin{bmatrix}\theta_c\\ \dot\theta_c\\ \gamma_c\end{bmatrix}+\begin{bmatrix}0\\ 0.25\\ 0\end{bmatrix}w$$

or

$$\dot{x}_c(t)=A_c x_c(t)+e_c w(t) \tag{6}$$

where w is a zero mean, Gaussian white noise process.

Aggregating equations (1), (2), (3), and (6) allows the command/vehicle system to be expressed in the form

$$\dot{x}(t)=Ax(t)+bu_p(t)+ew(t) \tag{7}$$

$$y_p(t)=Cx(t)+du_p(t)+v(t) \tag{8}$$

for $x^T(t)=[x_c^T(t),x_v^T(t),x_k^T(t)]$ and the obvious definitions for A, b, e, C, and d. Finally, the pilot model observation vector y_p is taken as

$$y_p^T=[\gamma_e,\dot\gamma_e,\gamma,\dot\gamma,\theta,\dot\theta] \tag{9}$$

where $\gamma_e=\gamma_c-\gamma$. Using these observations to solving for the optimal-control pilot model leads to the block diagram description of the pilot/vehicle system shown in Fig. 2. Here the cross-hatched blocks represent pilot compensation in his control loops.

More detailed development and description of the methodology can be found in Refs. (5) and (6). It will only be necessary to outline a few pertinent points here. The optimal-control pilot model uses the time-domain description of the pilot's sensing and response limitations. Statistical representation of these limitations, relevant to this report, are summarized in Table 3.

It could be argued that the pilot perceives flight-path information from visual cues such as the vehicle's sink rate, and that flight-path rate might be detected through acceleration cues at the cockpit. However, for want of better information concerning how the pilot extracts flight path information from available motion and display cues, flight-path-angle and flight-path-rate perception thresholds were chosen identical to the pitch attitude thresholds discussed in Schmidt.[8] The value of τ_n, the pilot's neuromuscular lag time constant, was selected to represent the human operator's most aggressive control action. This is consistent with the analysis objective of exposing handling qualities "cliffs" in the flight configurations, which will require an attempt to model the pilot's most aggressive control techniques. Finally, the observation and motor noise statistics, along with the observation delay τ, were chosen consistent with the optimal control pilot model studies reported in Refs. (4) and (5).

The coherent part of the pilot's control response can be described in terms of a pilot transfer matrix defined by

$$u_p(s) = H(s)\, y_p(s) \tag{10}$$

The pilot transfer matrix is obtained directly from the optimal control solution

$$H(s) = \frac{-l_e}{\tau_n s + l}\left[(sI - \hat{A})\int_0^{\tau} e^{(sI - A_1)\sigma} d\sigma (sI - A_1 + b_1 l_e) + sI - \hat{A} + b_1 l_e\right]^{-1} \Sigma_1 C_1^T V^{-1} \tag{11}$$

with

$$\begin{bmatrix} A & b \\ 0 & 0 \end{bmatrix}^T K + K\begin{bmatrix} A & b \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} Q & 0 \\ 0 & r \end{bmatrix} - \frac{1}{g} K \begin{bmatrix} 0 \\ I \end{bmatrix} [0 \quad I] K = 0$$

$$\dot{u}_p = \frac{1}{g}[0 \quad I] K \begin{bmatrix} x \\ u_p \end{bmatrix} = \frac{1}{\tau_n} 1_e \hat{x} - \frac{1}{\tau_n} u_p$$

$$A_1 = \begin{bmatrix} A & b \\ 0 & -1/\tau_n \end{bmatrix}, \quad b_1 = \begin{bmatrix} 0 \\ 1/\tau_n \end{bmatrix}$$

$$C_1 = [C \quad d]$$

and

$$\hat{A} = A_1 - \Sigma_1 C_1^T V^{-1} C_1$$

Also, Σ_1 is the steady state error covariance associated with the Kalman estimator, and V is the pilot model observation noise intensity.

For the critical task as modeled, the pilot control input can be expanded in terms of the pilot transfer function matrix and pilot observations

$$u_p(s) = \left[H_{\gamma e}(s) + sH_{\dot{\gamma} e}(s)\right]\gamma_e(s) + \left[H_\gamma(s) + sH_{\dot{\gamma}}(s)\right]\gamma(s) + \left[H_\theta(s) + sH_{\dot{\theta}}(s)\right]\theta(s) \tag{12}$$

where, for example, the Laplace Transform definition

$$L\{\dot{\theta}(t)\} = s\theta(s)$$

has been used for the angular rates. An effective pilot transfer function, associated with some pilot observation η, can now be defined by

$$P_\eta(s) = H_\eta(s) + sH_{\dot{\eta}}(s)$$

so that the pilot's control input becomes a linear combination of effective pilot transfer functions and observations, or finally

$$u_p(s) = P_{\gamma e}(s)\gamma_e(s) + P_\gamma(s)\gamma(s) + P_\theta(s)\theta(s) \tag{13}$$

The preceding pilot control equation is, of course, reflected in the block diagram representation of the flight-path-tracking task previously introduced (see Fig. 2). An example of the effective pilot frequency responses for LAHOS Configuration 2-2 is shown in Fig. 3. With these frequency responses of the effective pilot transfer functions now available, discussion will turn to closed-loop analysis of the handling characteristics of the LAHOS configurations.

Analysis and Results

The actual analysis consists first of an evaluation of the attitude dynamics alone, using a variation of the Bacon and Schmidt[5] procedure; the intent being that undesirable attitude dynamics should be exposed at the outset. The hypothesis is that for aircraft in which flight-path is controlled by pitch-attitude, some definition and evaluation of the minimum ability to control attitude is necessary, even though flight-path control is the ultimate goal. Neal and Smith, as well as Bacon and Schmidt, were able to analyze the pilot/vehicle handling-quality-criteria problem in the attitude control task as a trade-off between pilot workload required to achieve acceptable task performance and a subsequent measure of the pilot/vehicle closed-loop performance. Traditionally, pilot workload has been shown to correlate with the required pilot phase equalization.

Bacon and Schmidt, like Neal and Smith, used the pilot's phase compensation at the closed-loop bandwidth frequency to quantify the pilot's task workload in the attitude tracking task. They also used the magnitude of the resonant peak of the closed-loop θ/θ_c frequency response as a gauge of closed-loop performance and stability. In both analysis procedures, however, some limit was selected on the maximum allowable "low-frequency droop" of the closed-loop frequency response.

Table 3 Pilot model parameters

Parameter	Value
Observation vector	$y_p^T = [\gamma_e, \dot{\gamma}_e, \gamma, \dot{\gamma}, \theta, \dot{\theta}]$
Objective function weights	$q_{ii} = [1,0,0,0,0,0]$ $r_{F_s} = 0$
Observation thresholds	$T_{\gamma_e,\gamma,\theta} = 0.05$ deg $T_{\dot{\gamma}_e,\dot{\gamma},\dot{\theta}} = 0.18$ deg/s
Observation noise ratio	-20 dB all observed variables
Fractional attention	$f_i = 0.3333$ all observed variables
Observation delay	$\tau = 0.2$ s
Neuromuscular lag	$\tau_n = 0.1$ s
Motor noise variance	-25 dB
Control input	F_s (stick force in lb)

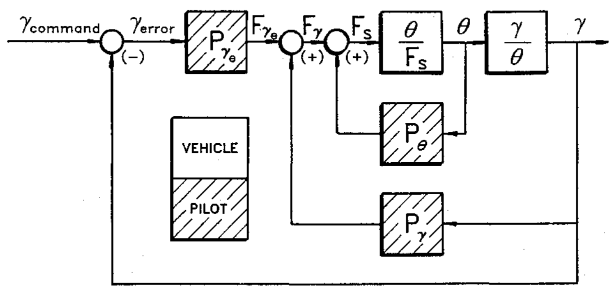

Fig. 2 The multiloop flight path tracking task.

More recently, Waszak and Schmidt[9] have been able to characterize the closed-loop performance of the pilot/vehicle system through the use of a sensitivity parameter established to evaluate the change in closed-loop resonant peak due to a small change (10%) in the pilot/vehicle forward path gain. This sensitivity parameter, defined by

$$\mathrm{SP} = (\text{low frequency droop})\left[\frac{\Delta\,\text{resonant peak}}{\Delta\,\text{pilot gain}}\right] \tag{14}$$

gave results, indicated in Fig. 4, for the original Neal-Smith pitch-attitude-tracking configurations that were also evaluated by Bacon and Schmidt.[5]

Applying this pitch-attitude-tracking modeling methodology to the LAHOS data set reveals the results shown in Fig. 5. From a comparison of Fig. 4 and Fig. 5, it is obvious that the LAHOS configurations are grouped nicely, in terms of Level 1, 2, and 3 ratings for the landing task, but that higher pilot phase compensation is required in the LAHOS data set as compared to the Neal-Smith configurations (and the attitude tracking task). This difference is of course consistent with lower short-period frequencies corresponding to the lower airspeeds encountered in the landing phase that thereby require the pilot to generate more phase lead in landing than in an up-and-away flight condition. However, by the placement of the pilot-rated Level 1 region in Fig. 5, one can conclude that the pilot actually accepts the higher required phase compensation in the landing task, while the same phase requirement would result in a Level 2 rating in a pure attitude tracking task. It is clear, therefore, that although the ratings of the configurations in the landing task correlate well with the resonance-peak sensitivity and phase compensation, the Neal-Smith criteria cannot be directly applied to infer or predict ratings in the landing task. Adjustments in the allowable phase compensation and peak sensitivity (or peak) consistent with the results of Fig. 5 are suggested.

Attention is now turned toward the analysis of the LAHOS database in the critical flight-path tracking task. In this task, however, directly identifying the pilot's phase compensation is not easily accomplished with the current multiloop block diagram arrangement. However, the block diagram in Fig. 2 can be manipulated, using the results from Fig. 3, for example, to give an equivalent single-loop representation, as shown in Fig. 6.

Figure 7 illustrates the *equivalent* single-loop pilot function, $P_{eq}(s)$, for LAHOS Configuration 2-2, obtained from the vehicle dynamics and from the data in Fig. 3. From this figure, one can readily see that the pilot is required to generate a significant amount of lead near 3.5 rad/s in the flight-path-

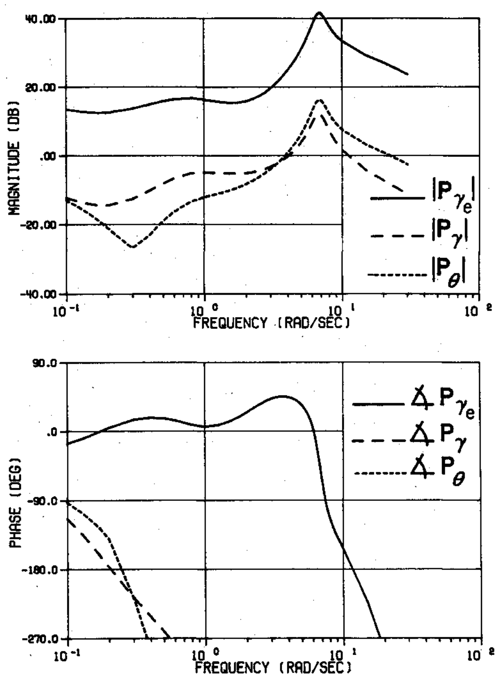

Fig. 3 Configuration 2-2 effective pilot transfer functions.

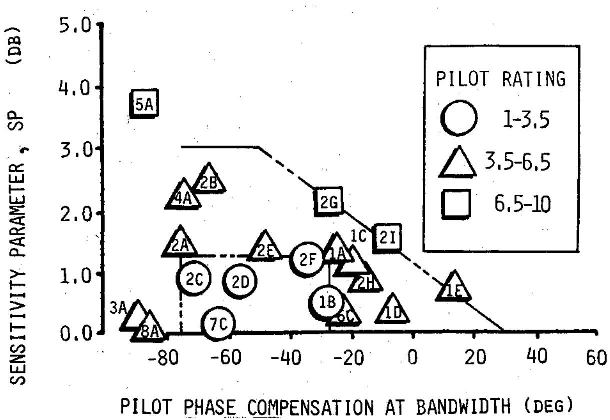

Fig. 4 Neal-Smith/Waszak-Schmidt pitch attitude tracking results.

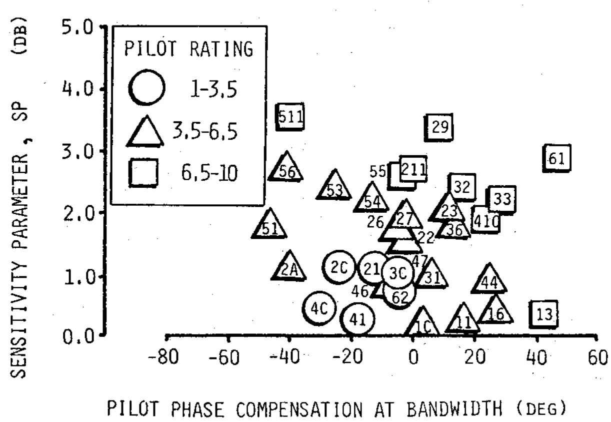

Fig. 5 LAHOS Configurations pitch attitude tracking results.

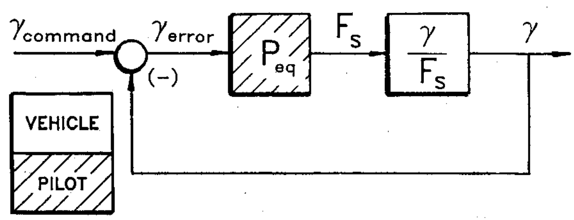

Fig. 6 Flight path tracking with equivalent pilot function.

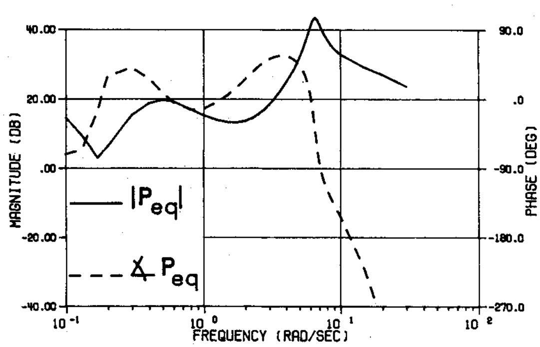

Fig. 7 Configuration 2-2 equivalent single-loop pilot function.

tracking task in order to stabilize and maximize the tracking performance of the closed-loop, pilot/vehicle system. The lead generated (maximum equivalent phase peak) is again suggested as a model-based indication of pilot workload.

Bacon and Schmidt also advanced the use of maximum achievable closed-loop bandwidth as an indicator of the combined pilot/vehicle system's ability to track over the frequency band. Bandwidth is defined here, as per Neal and Smith, as the frequency at which the closed-loop phase equals -90 deg. The closed-loop bandwidth, determined from the combined pilot/vehicle system, depends, of course, upon both the vehicle and pilot dynamics (particularly the neuromotor lag time constant τ_n). As the pilot model parameters have been held constant for all configurations studied, and the smallest achievable τ_n has been assumed, insufficient achievable bandwidth is directly related to sluggish vehicle response. Results shown in Fig. 8 verify that low comparative path bandwidth correlates with higher (worse) pilot ratings. However, once sufficient bandwidth is attainable, other methods must be applied to uncover handling quality deficiencies.

One of the most important aspects of closed-loop performance is the stability robustness of the loop itself. Stability robustness, here interpreted as insensitivity to small changes in pilot compensation, can best be measured using the combined pilot/vehicle open-loop Bode, or frequency response. Figure 9, for example, shows the open- and closed-loop frequency responses for LAHOS Configuration 2-2.

From Fig. 9 one can see a magnitude peak evident in the open-loop frequency response at a frequency just greater than the phase crossover frequency. A Nyquist diagram of the same open-loop response (see Fig. 10) illustrates that any small phase or gain change injected by the pilot could cause an instability in this system. The magnitude of this peak, as defined in Fig. 9, herein entitled the *high-frequency open-loop peak*, is therefore a measure of loop quality, due to its close association with loop stability robustness properties. For comparison, Fig. 10 also shows the Nyquist contour for Configuration 2-1, which received a better rating in the task.

The genesis of this peak is also significant. Figure 11 shows the frequency response of the LAHOS Configuration 2-2 flightpath to stick-force transfer function. Considering this figure and the equivalent pilot function shown in Fig. 7, one can readily see that the high-frequency open-loop peak in the $\gamma/\gamma_e(s)$ response (in Fig. 9) is due solely to the magnitude distortion arising from the pilot's frequency response. As in any dynamic lead-lag compensator design, magnitude distortion of this type will develop when the compensator is required to achieve significant phase lead.

By observing the phase of the flight-path response in Fig. 11, along with noting the fact that the pilot is band-limited with his own time delay, it becomes clear why significant phase lead is required. The high frequency magnitude and phase distortion in the equivalent pilot function, which in the past has been attributed to the pilot's neuromuscular dynamics,[10] can be readily explained in this situation from a purely control theoretic viewpoint. Consider a band-limited dynamic compensator designed to meet the tracking system objective of maximizing closed-loop bandwidth. In this case, the pilot can be thought of as the dynamic compensator, band-limited by his own inherent neuromotor lag. The critical nature of the approach and landing task provides impetus for the pilot's desire to maximize the closed-loop flight-path tracking performance in order to gain precise control over the aircraft's sink rate. Finally, adequate gain and phase margins must be maintained (see Fig. 10) for overall system stability. Therefore, any control system designed to meet the previously stated objectives would have characteristics similar to the pilot describing function shown in Fig. 7. Finally, it is worth noting that similar high frequency magnitude peaks have actually been experimentally measured[11] where plants with time delay (low phase) were being evaluated.

A plot of the high-frequency open-loop peak versus maximum pilot phase compensation, as shown in Fig. 12, reveals a characteristic grouping of the vehicle configurations not unlike those of Refs. 2, 5, and 9. Those configurations that were rated best overall (Cooper-Harper Level 1) in the *approach*

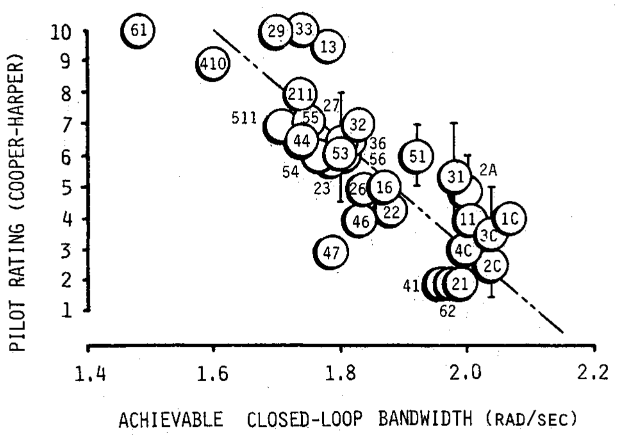

Fig. 8 Pilot rating and path bandwidth correlation.

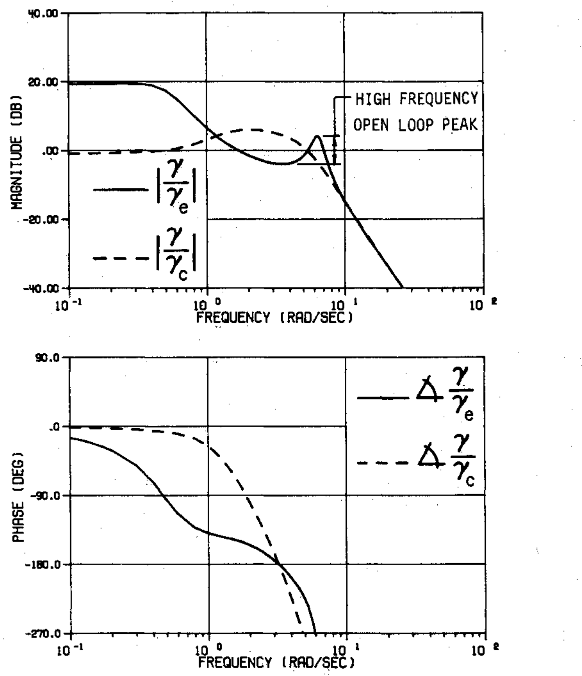

Fig. 9 Configuration 2-2 open- and closed-loop frequency responses.

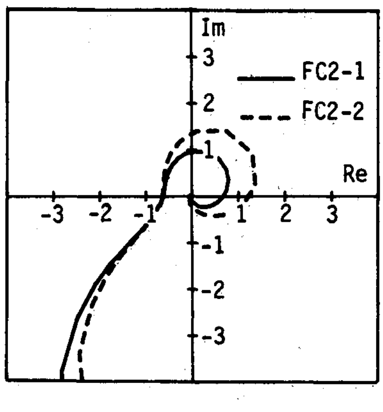

Fig. 10. Nyquist diagram for Configurations 2-1 and 2-2.

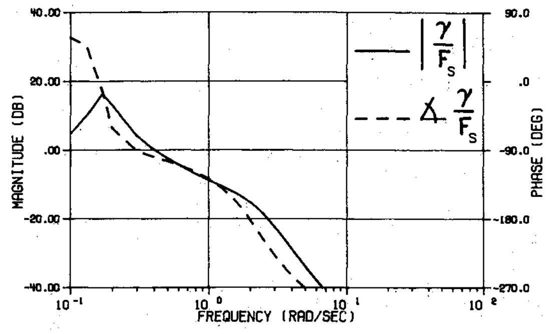

Fig. 11 Configuration 2-2 flight path to stick force frequency response.

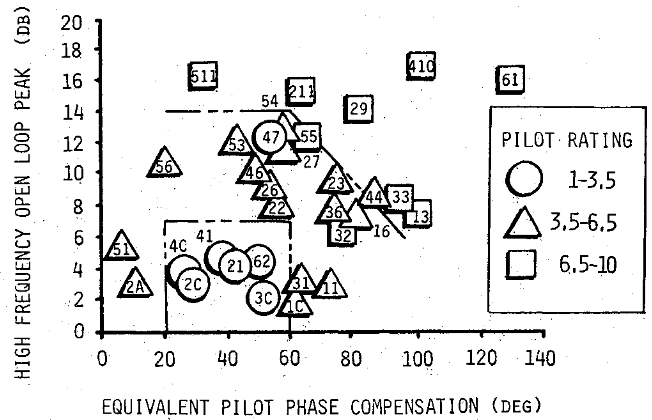

Fig. 12 High frequency open-loop peak results for the flight path tracking task.

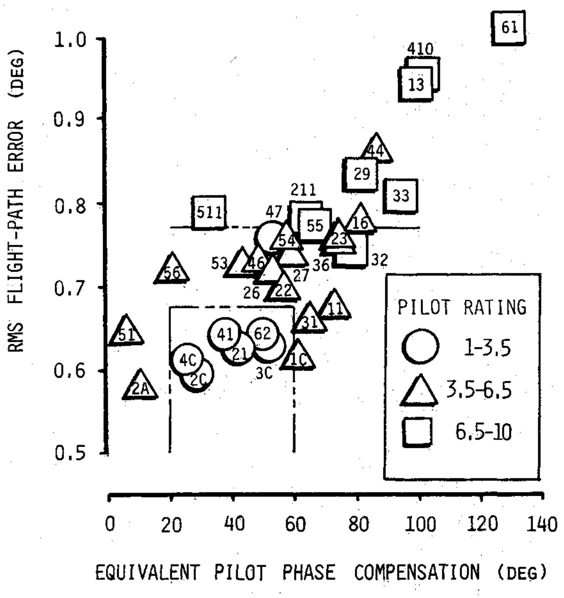

Fig. 13 RMS flight-path error results.

and landing task are appropriately grouped together. The pilot-phase-compensation results for these vehicle configurations indicate that a certain amount of effective phase lead is also acceptable to the pilot in the flight-path-tracking task. Those configurations that were rated poorly (Levels 2, 3) in the approach and landing task would appear to suffer from insufficient loop quality, as measured by the high-frequency open-loop peak, and/or excessive pilot workload.

An additional evaluation of loop quality stems from the critical task definition—to minimize flight-path error. In fact, the time-domain minimization of error has been used as a loop performance measure in several past efforts.[12-15] The steady-state, root-mean-squared flight-path error, obtained directly from the optimal pilot modeling method, can also be used as a quantitative measure of loop performance. Figure 13 illustrates another appropriate grouping of the 32 flight configurations where rms flight-path error is used to indicate loop quality and the maximum pilot phase compensation is again used as a workload metric.

Conclusion

An optimal-control/frequency-domain (OC/FD) methodology is presented, which is intended as a dynamic handling-qualities analysis tool appropriate for such complex, multiloop, man-machine tasks as aircraft approach, flare, and landing. When an analysis of just the pitch-attitude tracking ability was performed on the landing-task database (LAHOS), a grouping of the configurations similar to the Neal-Smith results was obtained. However, direct application of the Neal-Smith criteria does not appear appropriate for estimating the ratings in the landing task since, among other things, the pilot appears to accept higher phase compensation requirements in the landing task. The proposed technique for such an attitude analysis is a variation of the method of Bacon and Schmidt, which does not require any selection of closed-loop "droop" or closed-loop bandwidth to perform the analysis.

A critical flight-path control task was developed, and when a closed-loop analysis of this task was performed using the LAHOS database, excellent correlation was obtained with several model-based quantities of engineering significance. First, correlation was evident between the ratings of the configurations in the landing task and the maximum achievable closed-loop bandwidth obtained from closed-loop analysis of the critical task. Also, strong correlation was noted between the ratings and the pilot-phase-compensation, as modeled, and the two proposed measures of loop quality, all of which result from the closed-loop analysis technique. The pilot-phase compensation associated with a single analytically obtained describing function, dynamically equivalent to the multiloop model, was suggested as a workload metric. A high-frequency open-loop peak, related to stability robustness, and direct estimates of rms flight-path error were recommended as loop performance measures. Finally, the quantities used in this analysis technique are fundamental in linear systems analysis and are aimed at providing significant insight into the causes of, and remedies for, unacceptable man-machine system characteristics.

Acknowledgments

This work has been sponsored by the NASA Dryden Flight Research Facility/Ames Research Center under Grant NAG4-1. Mr. Donald T. Berry is the technical monitor. This support is gratefully appreciated. Also, a significant portion of the software development and early conceptual ideas was attributable to Mr. Dan Garrett while he was a graduate student in the School of Aeronautics and Astronautics. Mr. Garrett is now with McDonnell Aircraft Company, St. Louis, Missouri.

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