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**SIMULATED LANDING APPROACHES OF AN  
UNAUUGMENTED C-5A CONFIGURATION**

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FOREWORD

This report was prepared for the United States Air Force by Cornell Aeronautical Laboratory, Inc. (CAL), Buffalo, New York in partial fulfillment of Contract AF33(615)-2411.

The work reported herein was performed by the CAL Flight Research Department under the sponsorship of the Air Force Flight Dynamics Laboratory, Research and Technology Division (RTD), Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, as Project No. 8219, Stability and Control Investigations, Task No. 821905, Handling Qualities Requirements. The RTD project engineer has been Mr. R.O. Sickeler.

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## ABSTRACT

Expected ranges of unaugmented longitudinal and lateral-directional handling qualities of the C-5A class airplane were simulated and evaluated in a variable-stability B-26 for the instrument-landing task. The longitudinal short period undamped frequency was given three values, 0.064, 0.10, and 0.16 cps, and a short period damping ratio of 0.7 was maintained. The elevator stick force and stick motion gradients were given two values each -- 60 lb/g and 100 lb/g, and 8 in./g and 2 in./g, respectively. The lateral-directional parameters  $\left(\frac{pb}{2u}\right)$  and  $\tau_R$  were each given values of 0.08, 0.14, and 0.22 for  $\left(\frac{pb}{2u}\right)_{max}$  and 0.6, 1.0, and 1.4 for  $\tau_R$ . Although many of the configurations were judged to be acceptable, none were satisfactory, thus implying that stability augmentation is probably required.

# Contrails

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## SYMBOLS

$$D_V = \frac{1}{m} \left[ \rho V_0 S C_{D_0} - \frac{\partial T}{\partial V} \right]$$

$$D_\alpha = \frac{1}{m} \left[ \bar{q} S C_{D_\alpha} + T \alpha_0 - W \right]$$

$$D_\theta = g \cos \gamma_0 \approx g$$

$$D_{\delta_T} = \frac{1}{m} \frac{\partial T}{\partial \delta_T}$$

$$L_\alpha = \frac{\rho V S}{2m} C_{L_\alpha}$$

$$M_\alpha = \bar{q} \frac{S \bar{c}}{I_Y} C_{m_\alpha}$$

$$M_{\dot{\alpha}} = \bar{q} \frac{S \bar{c}^2}{2 I_Y V_0} C_{m_{\dot{\alpha}}}$$

$$M_\theta = \frac{\bar{q} S \bar{c}}{I_Y} C_{m_\theta}$$

$$M_{\dot{\theta}} = \bar{q} \frac{S \bar{c}^2}{2 V_0 I_Y} C_{m_{\dot{\theta}}}$$

$$M_u = \frac{\rho S V \bar{c}}{I_Y} (C_m + C_{m_u})$$

$$M_{\dot{u}} = \frac{\rho u^2 S \bar{c}}{2 I_Y} C_{m_{\dot{u}}}$$

$$M_{\delta_c} = \frac{\bar{q} S \bar{c}}{I_Y} C_{m_{\delta_c}}$$

$$\beta_\alpha = -\frac{1}{m V_0} \left[ (\alpha_0 C_{D_\alpha} + C_{L_\alpha}) \bar{q} S + T_0 - W \theta_0 \right]$$

$$\beta_{\dot{\alpha}} = \cos \alpha_0$$

$$\beta_\theta = -\frac{g \theta_0}{V_0}$$

$$\beta_{\dot{\theta}} = \cos \alpha_0$$



# Contrails

## SYMBOLS (Cont.)

$$\bar{z}_v = -\frac{\rho S}{m} [C_{L_0} + \alpha_0 C_{D_0}]$$

$$\bar{z}_i = \frac{\sin \alpha_0}{V_0}$$

$$\bar{z}_{\delta e} = -\frac{\bar{q} S}{m V_0} C_{L \delta e}$$

$$Y_B = \frac{\rho S U}{2m} C_{Y_B}$$

$$Y_P = \frac{\rho S b}{4m} C_{Y_P}$$

$$Y_r = \frac{\rho S b}{4m} C_{Y_r}$$

$$Y_{\delta r} = \frac{\rho S U}{2m} C_{Y_{\delta r}}$$

$$L_B = \frac{\rho S U^2 b}{2I_x} C_{L_B}$$

$$L_P = \frac{\rho S U b^2}{4I_x} C_{L_P}$$

$$L_r = \frac{\rho S U b^2}{4I_x} C_{L_r}$$

$$L_{\delta r} = \frac{\rho S U^2 b}{2I_x} C_{L_{\delta r}}$$

$$L_{\delta a} = \frac{\rho S U^2 b}{2I_x} C_{L_{\delta a}}$$

$$N_B = \frac{\rho S U^2 b}{2I_z} C_{N_B}$$

$$N_P = \frac{\rho S U b^2}{4I_z} C_{N_P}$$

$$N_r = \frac{\rho S U b^2}{4I_z} C_{N_r}$$

$$N_{\delta a} = \frac{\rho S U^2 b}{2I_z} C_{N_{\delta a}}$$

$$N_{\delta r} = \frac{\rho S U^2 b}{2I_z} C_{N_{\delta r}}$$

# Contrails

## SYMBOLS (Cont.)

$b$	=	wing span = 219 ft
$\bar{c}$	=	mean aerodynamic chord = 30.41 ft
$F_{Es}$	=	elevator stick force
$f_{n_{SP}}$	=	short period undamped natural frequency, cps
$g$	=	32.2 ft/sec <sup>2</sup>
$\dot{h}$	=	airplane sink rate, fps
$\dot{h}_m$	=	model sink rate, fps
$K_{\theta m}$	=	model gain constant
$K_{q m}$	=	model gain constant
$m$	=	airplane mass = 18,160 slugs
$n_z$	=	normal acceleration $\sim$ g units
$\bar{q}$	=	aerodynamic pressure = $\frac{1}{2} \rho V^2$
$\dot{\theta}$	=	pitch rate
$\dot{\theta}_m$	=	model pitch rate
$\dot{\theta}_a$	=	airplane pitch rate
$\ddot{\theta}$	=	pitch acceleration
$n$	=	yaw rate
$\frac{pb}{2u}$	=	wing tip nondimensional velocity
$T$	=	thrust

## SYMBOLS (Cont.)

$U=V$	=	forward velocity
$\dot{V}$	=	forward acceleration
$\Delta V$	=	perturbation velocity
$\alpha$	=	angle of attack
$\beta$	=	angle of sideslip
$\gamma$	=	flight path angle
$\delta_{ES}$	=	elevator stick motion
$\delta_{AS}$	=	aileron stick motion
$\delta_a$	=	aileron motion
$\delta_{RP}$	=	rudder pedal motion
$\delta_r$	=	rudder motion
$\theta$	=	pitch angle
$\theta_m$	=	model pitch angle
$\theta_a$	=	airplane pitch angle
$\dot{\theta}$	=	pitch rate
$\phi$	=	bank angle
$\phi_1$	=	bank angle achieved at end of one second for full aileron command
$\zeta_{SP}$	=	short period damping ratio
$\omega_{\kappa_{SP}}$	=	short period undamped natural frequency, rad/sec
$\zeta_P$	=	phugoid damping ratio
$\omega_{\kappa_P}$	=	phugoid undamped natural frequency, rad/sec

## SYMBOLS (Cont.)

$\zeta_d$  = Dutch-roll damping ratio

$\omega_{nd}$  = Dutch-roll undamped natural frequency, rad/sec

$\tau_R$  = roll mode time constant

$\tau_s$  = spiral mode time constant

$$C_D = \frac{D}{qS}$$

$\rho$  = air density

$$C_{D\alpha} = \frac{\partial C_D}{\partial \alpha}$$

$$W = mg$$

$L_0$  = equilibrium lift

$$C_{D\delta_e} = \frac{\partial C_D}{\partial \delta_e}$$

$$C_L = \frac{L}{qS}$$

$$C_{L\alpha} = \frac{\partial C_L}{\partial \alpha}$$

$$C_{L\delta_e} = \frac{\partial C_L}{\partial \delta_e}$$

$$C_{m\dot{\alpha}} = \frac{\partial C_m}{\partial \frac{d\alpha}{dt}}$$

$$C_{m\alpha} = \frac{\partial C_m}{\partial \alpha}$$

$$C_{m\dot{\alpha}} = \frac{\partial C_m}{\partial \frac{d\alpha}{dt}}$$

## SYMBOLS (Cont.)

$$C_{m\delta e} = \frac{\partial C_m}{\partial \delta e}$$

$$C_{mV} = \frac{V}{2} \frac{\partial C_m}{\partial V}$$

$$C_m = \frac{M}{q S c}$$

$$C_{m\dot{u}} = \frac{\partial C_m}{\partial \dot{u}}$$

$$C_{Y\beta} = \frac{\partial C_Y}{\partial \beta}$$

$$C_{Yp} = \frac{\partial C_Y}{\partial \frac{pb}{2u}}$$

$$C_{Yr} = \frac{\partial C_Y}{\partial \frac{rb}{2u}}$$

$$C_{Y\delta r} = \frac{\partial C_Y}{\partial \delta r}$$

$$C_{L\beta} = \frac{\partial C_L}{\partial \beta}$$

$$C_{Lp} = \frac{\partial C_L}{\partial \frac{pb}{2u}}$$

$$C_{Lr} = \frac{\partial C_L}{\partial \frac{rb}{2u}}$$

$$C_{L\delta r} = \frac{\partial C_L}{\partial \delta r}$$

$$C_{L\delta a} = \frac{\partial C_L}{\partial \delta a}$$

$$C_{n\beta} = \frac{\partial C_n}{\partial \beta}$$

$$C_{np} = \frac{\partial C_n}{\partial \frac{pb}{2u}}$$

$$C_{nr} = \frac{\partial C_n}{\partial \frac{rb}{2u}}$$

# Contrails

## SYMBOLS (Cont.)

$$C_{n\delta_a} = \frac{\partial C_n}{\partial \delta_a}$$

$$C_{n\delta_r} = \frac{\partial C_n}{\partial \delta_r}$$

### Subscripts

*T* Throttle

*o* Equilibrium

*ss* Steady State

## SECTION 1

### INTRODUCTION

An in-flight simulation program has been conducted to evaluate certain anticipated flying qualities characteristics of a very large, logistics-type airplane. Certain longitudinal and lateral-directional flying qualities of the C-5A class airplane (without stability augmentation) were simulated.

The results indicate that the unaugmented handling characteristics will not be the most satisfactory and that stability augmentation will be required for the airplane.

Simulation of the C-5A was accomplished in a variable-stability B-26 airplane. The longitudinal handling characteristics were simulated using a pitch-angle, model-following technique. The lateral-directional characteristics were simulated using the response feedback technique.

The characteristics simulated were based upon a set of representative stability derivatives supplied by the Air Force. These derivatives do not represent any specific C-5A, but they are indicative of the expected values for this class of airplane.

For the longitudinal characteristics, the phugoid mode was maintained at a constant frequency and damping ratio. Three values of short-period frequency at a short-period damping ratio of 0.7 were evaluated as were two values of stick force per g and two values of stick motion per g.

The Dutch-roll mode and spiral were held constant for the lateral-directional evaluations for which the roll damping and roll power were varied.

No longitudinal configuration was, on the average, rated better than 3.5, and the best lateral-directional configuration was rated, on the average, 4.1. Five pilots evaluated each configuration tested.

# *Contrails*

Organization of this report follows the scheme of:

1. Longitudinal simulation by model-following techniques and lateral-directional simulation by response feedback techniques.
2. The manner in which the experiment was conducted.
3. The results of the experiment.
4. Conclusions.



## SECTION 2

### LONGITUDINAL SIMULATION

Longitudinal simulation was accomplished by the model-following, variable-stability technique. An analog computer was used to determine the responses of the simulated airplane, and the B-26 responses were made to follow one of these computed responses. The following discussion describes the model-following technique and its application for this simulation.

The pilot's input, rather than being applied directly to an aerodynamic control (e.g., the elevator) is converted to an electrical signal which is the input to the analog computer. Longitudinal equations of motion are wired into the computer. The computer solves these equations of motion and yields the time-history of the responses that result from the pilot's input. During the present simulation, one of these responses was compared electrically with the corresponding parameter measured directly in flight, and the electrical difference-signal between the two was obtained. This difference signal was used to drive the aerodynamic control surface of the airplane by a servo system.

The longitudinal simulation that was done for this program compared the computed pitch angle ( $\theta_m$ ) with the actual airplane pitch angle ( $\theta_a$ ). The difference between these pitch angles ( $\theta_m - \theta_a$ ) drove the elevator to make  $\theta_a$  equal to  $\theta_m$ . A second control loop, which deflected the elevator proportional to the difference between the computed and measured rate-of-change of pitch attitude ( $\dot{\theta}_m - \dot{\theta}_a$ ), was used in conjunction with the attitude-following loop to improve the tightness of the control. The elevator stick motion ( $\delta_{ES}$ ) was the input to the computer.

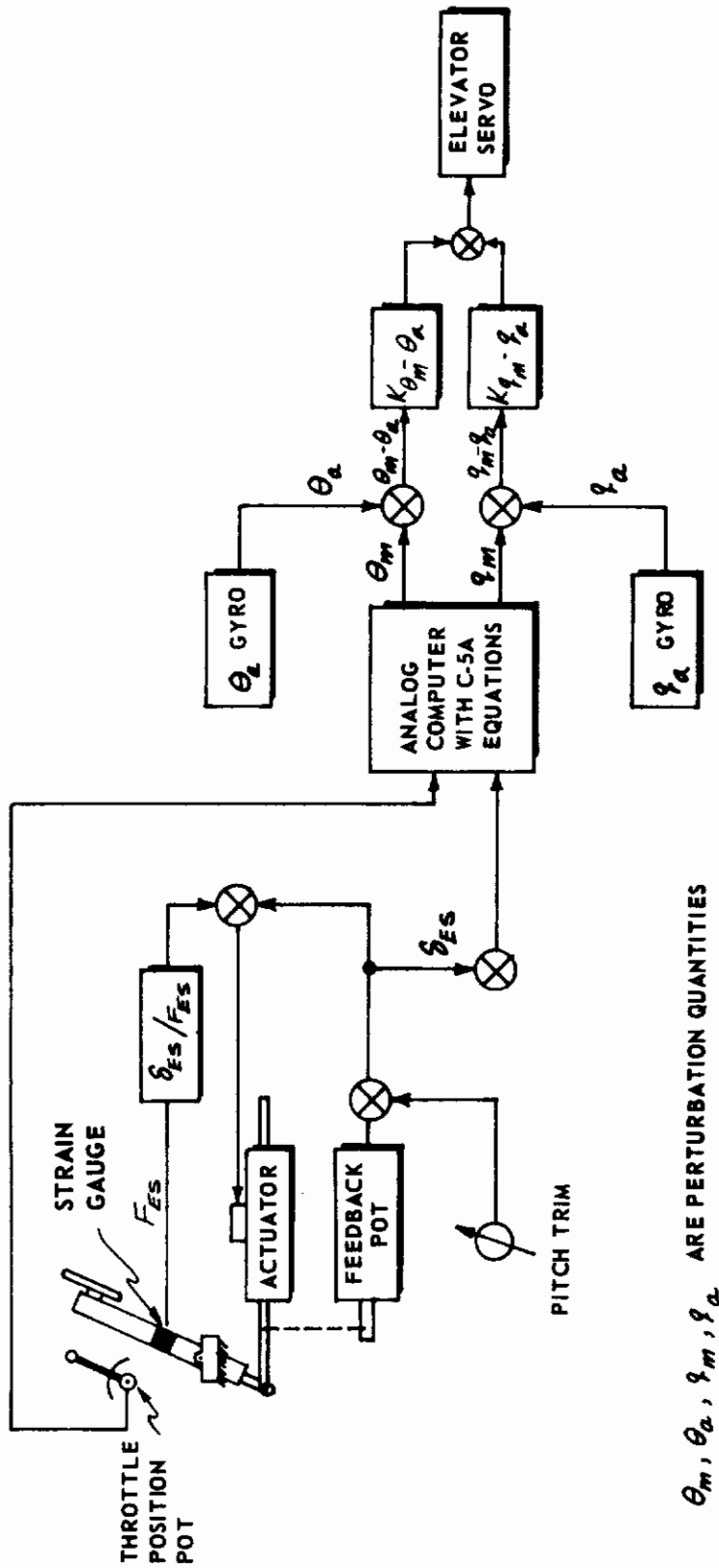
A computer system of this sort is said to be a model, and many airplanes can be represented by programming the appropriate equations on the computer. In this instance, the model was of the C-5A, and the B-26 elevator was driven to make the airplane pitch angle time-history the same as the C-5A pitch angle time history; that is,  $\theta_a = \theta_m$ . Thus, the complete name for this longitudinal simulation system is: "The pitch-angle, model-following system."

# Contrails

Other individual parameters could have been chosen for the matching process. There is only one servo-operated longitudinal control (the elevator) on this airplane, and, therefore, only one parameter can be matched during any given simulation. In this program, we chose the pitch angle and its rate to provide good pitch-angle following. The pitch angle is a very important pilot cue in the landing approach, particularly for instrument landings, where the pitch attitude indicator is a primary instrument and pitch attitude changes are large, which strongly suggests using pitch attitude following. The flight path is difficult to determine directly, and angle-of-attack or  $\alpha$  following is very susceptible to turbulence. The phugoid can be controlled with pitch-angle following, whereas it cannot be with angle-of-attack or  $\alpha$  following. Pitch-angle following avoids these problems. Figure 1 is a block diagram of the  $\theta$  model which shows a throttle input to the analog computer. The computed longitudinal response, therefore, includes the effects of the pilot's thrust commands insofar as the difference between thrust and drag is concerned. A thrust change does not cause a change in pitch angle because the model following system won't allow it. However, a thrust change will cause a change in speed which will cause the airplane to climb or dive. To stop the climb or dive, the pitch angle must be changed by either the stick or pitch trim knob.

The decision to use pitch-angle following for the simulation followed an analog computer study of pitch-angle following, angle-of-attack following, and a combination of the two methods. This study is reported in Reference 1.

Comparisons between the airplane pitch response and the model response time histories of pitch angle (both measured in flight) are presented in Figures 2 through 10. The three dynamic configurations that were evaluated during the program are represented by these figures (in three groups of three). The difference among the configurations is the value of the short-period undamped natural frequency. For all of the figures, the short-period damping ratio is 0.7, the phugoid frequency is 0.19 rad/sec, and the phugoid damping ratio is 0.05. The first figure of each set of three figures is for a synthetic elevator step input; that is, it is a perfect electrical step input introduced into the analog computer rather than from



$\theta_m, \theta_a, \varphi_m, \varphi_a$  ARE PERTURBATION QUANTITIES

Figure 1 MODEL-FOLLOWING SIMULATION TECHNIQUE

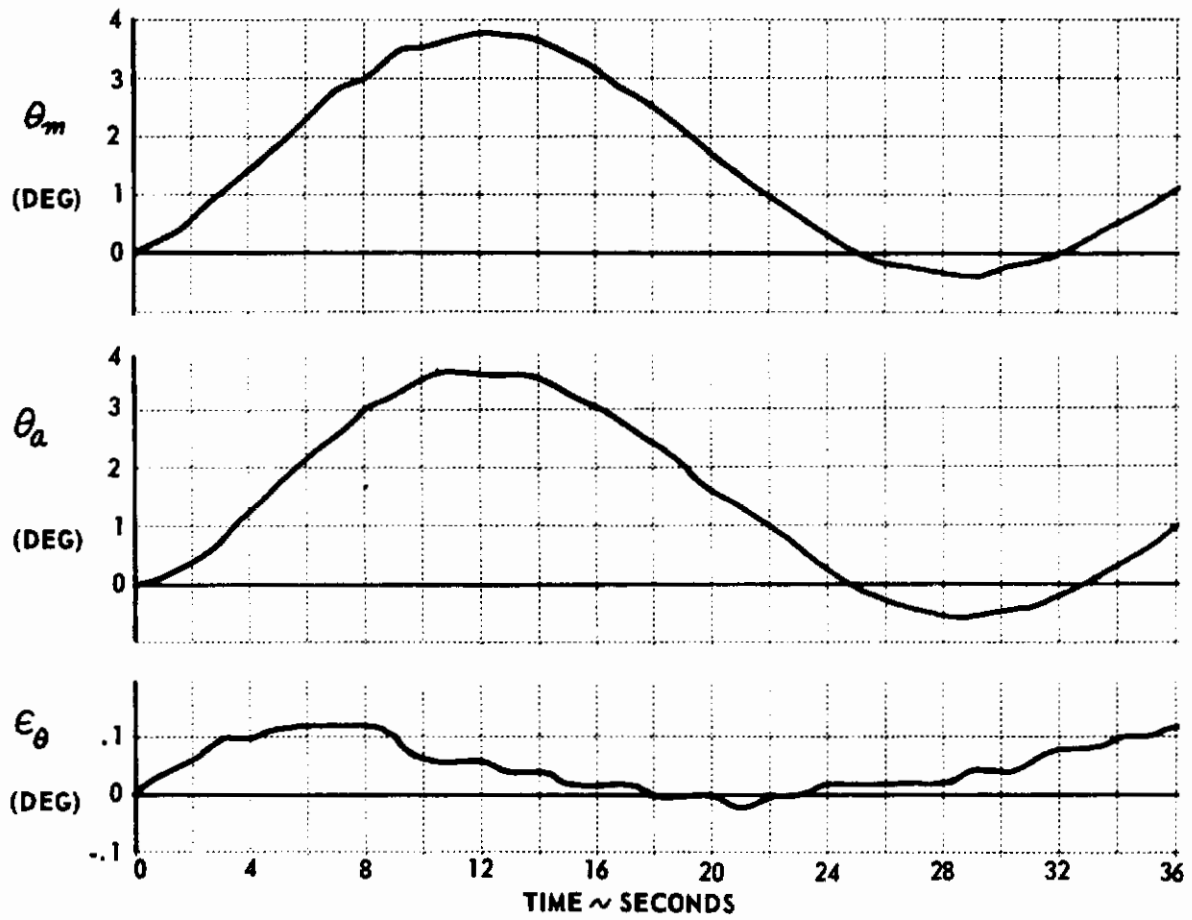


Figure 2 C-5A - MODEL-FOLLOWING CASE 4,  $\omega_{n_{sp}} = 0.4$  RAD/SEC  
 $\delta_e$  STEP  $\sim 2^\circ$  SYNTHETIC INPUT

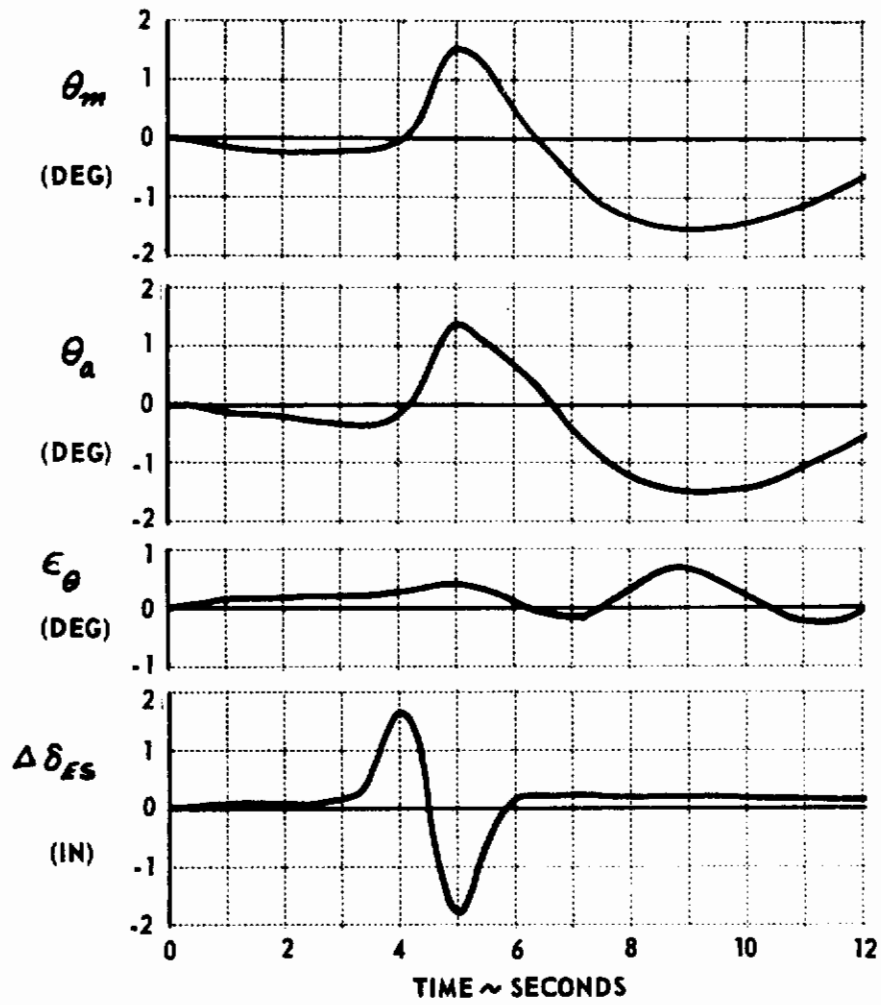


Figure 3 C-5A - MODEL-FOLLOWING CASE 4,  $\omega_{n_{SP}} = 0.4$  RAD/SEC FREE RESPONSE DOUBLET INPUT BY PILOT

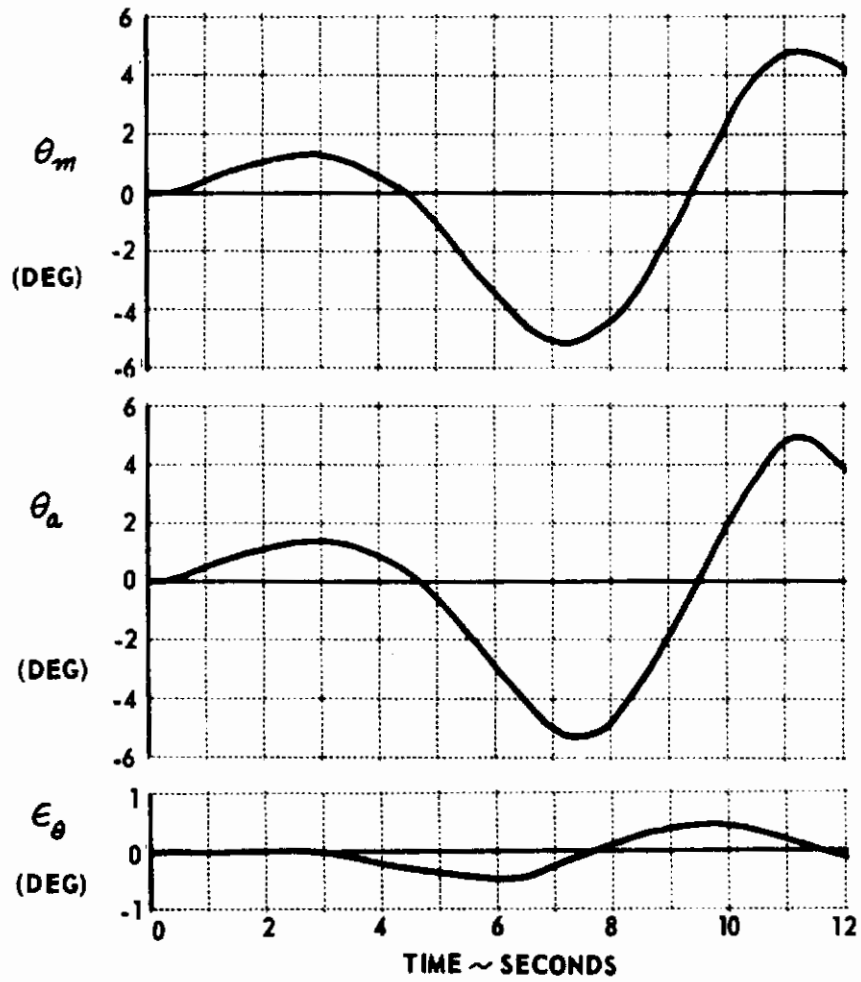


Figure 4 C-5A - MODEL-FOLLOWING CASE 4,  $\omega_{n_{sp}} = 0.4$  RAD/SEC FORCED RESPONSE FORCING INPUTS BY PILOT

# Contrails

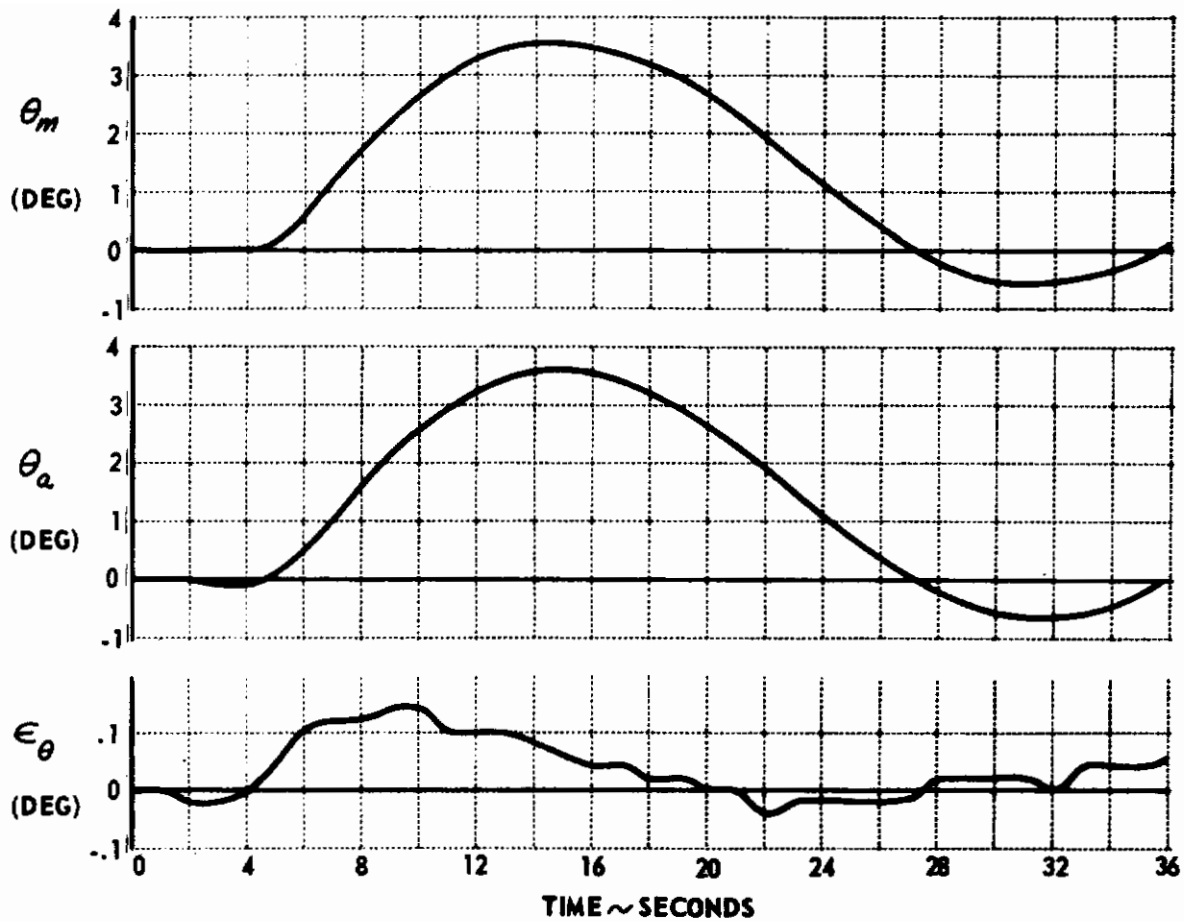


Figure 5 C-5A - MODEL-FOLLOWING CASE 5,  $\omega_{n_{SP}} = 0.628$  RAD/SEC,  $\delta_e$  STEP  $\sim 2^\circ$   
SYNTHETIC COMPUTER INPUT

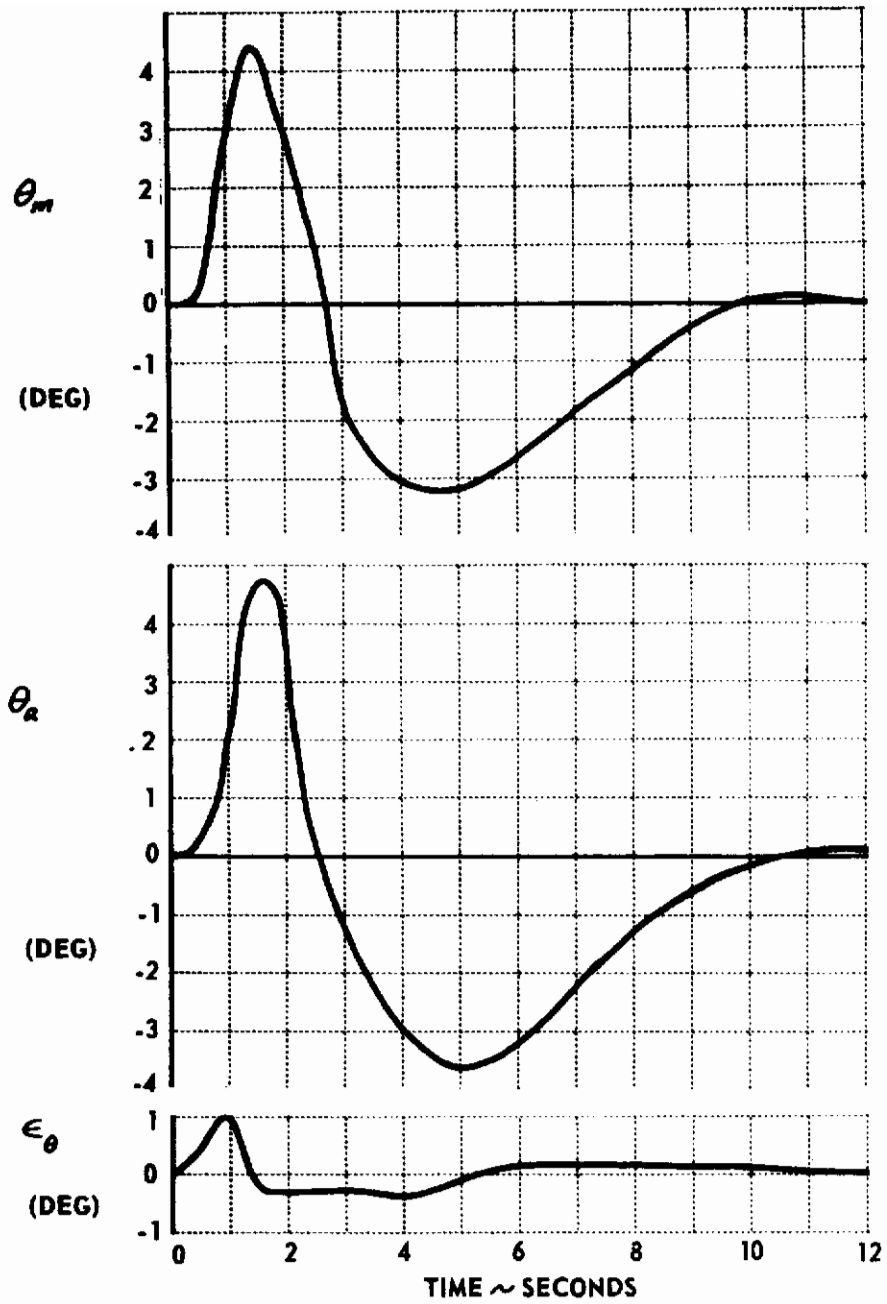


Figure 6 C-5A - MODEL-FOLLOWING CASE 5,  $\omega_{n_{SP}} = 0.628$  RAD/SEC FREE RESPONSE ELEVATOR DOUBLET BY PILOT



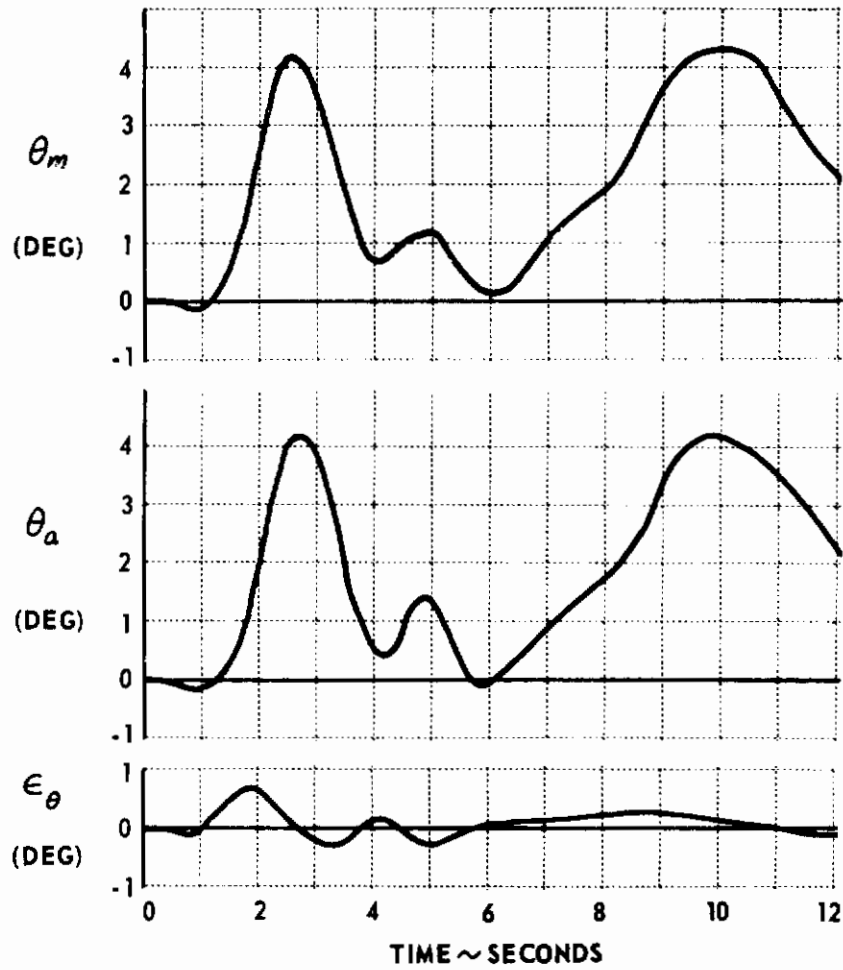


Figure 7 C-5A - MODEL-FOLLOWING CASE 5,  $\omega_{n_{sp}} = 0.628 \cdot \text{RAD/SEC}$  FORCED RESPONSE INPUT BY PILOT

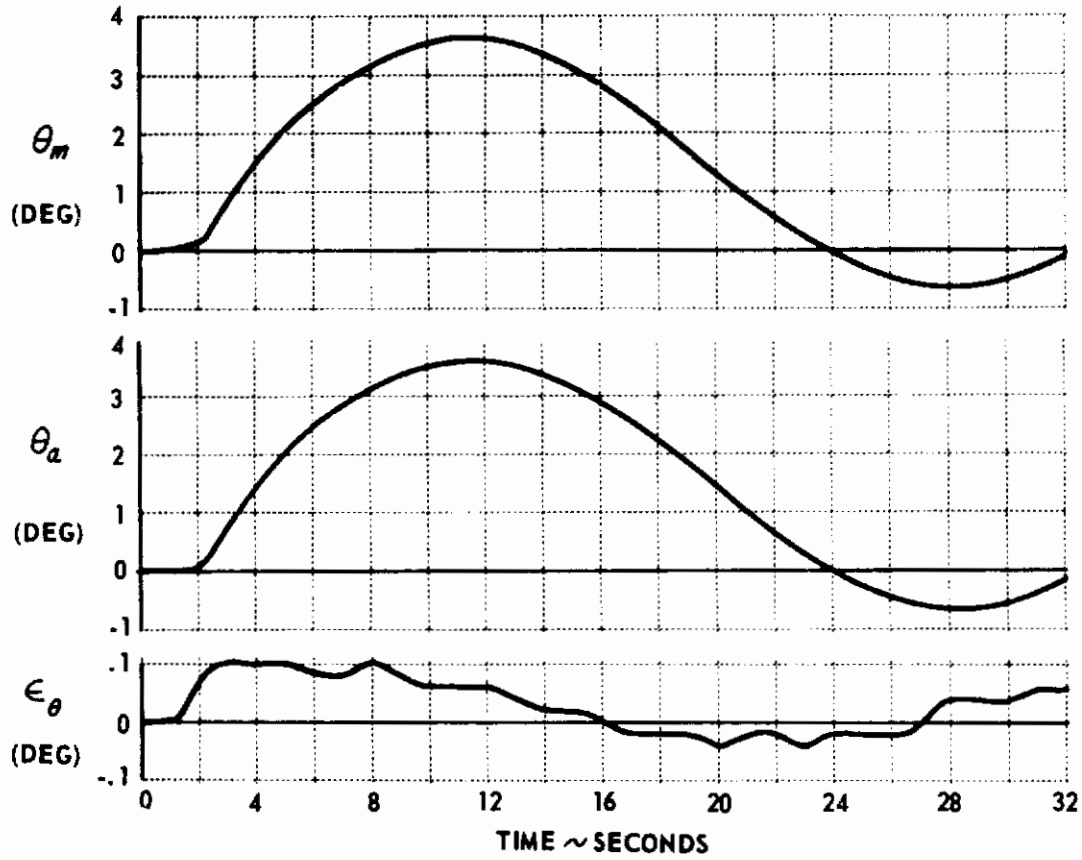


Figure 8 C-5A - MODEL-FOLLOWING CASE 6,  $\omega_{n_{sp}} = 1$  RAD/SEC  $\delta_e$  STEP  $\sim 2^\circ$   
SYNTHETIC INPUT

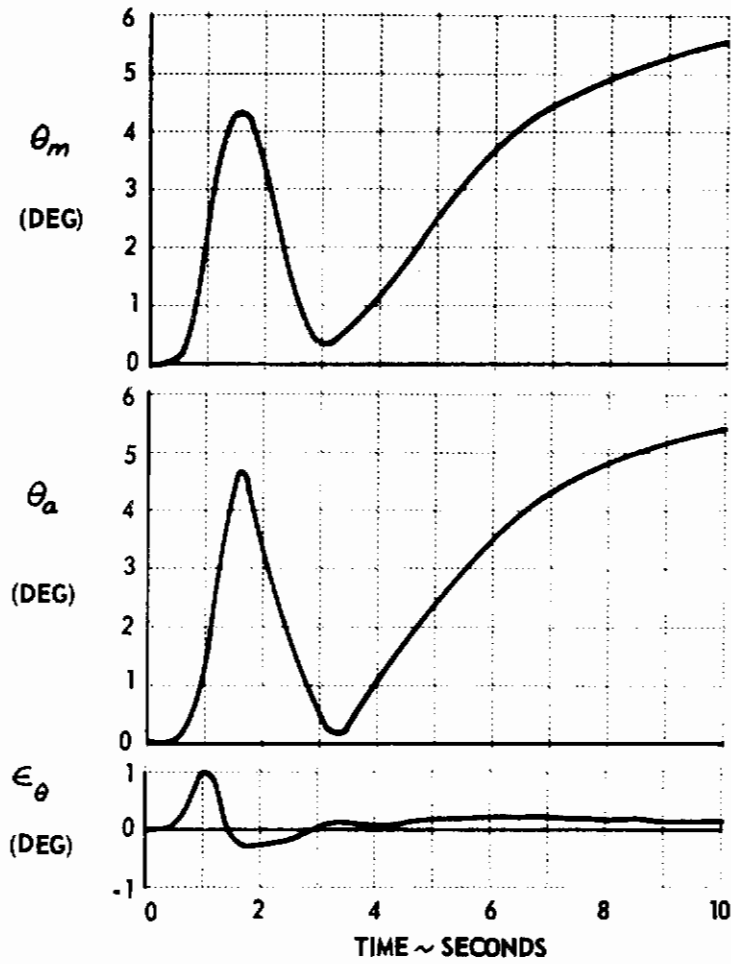


Figure 9 C-5A - MODEL-FOLLOWING CASE 6,  $\omega_{n_{SP}} = 1$  RAD/SEC FREE RESPONSE ELEVATOR DOUBLET BY PILOT

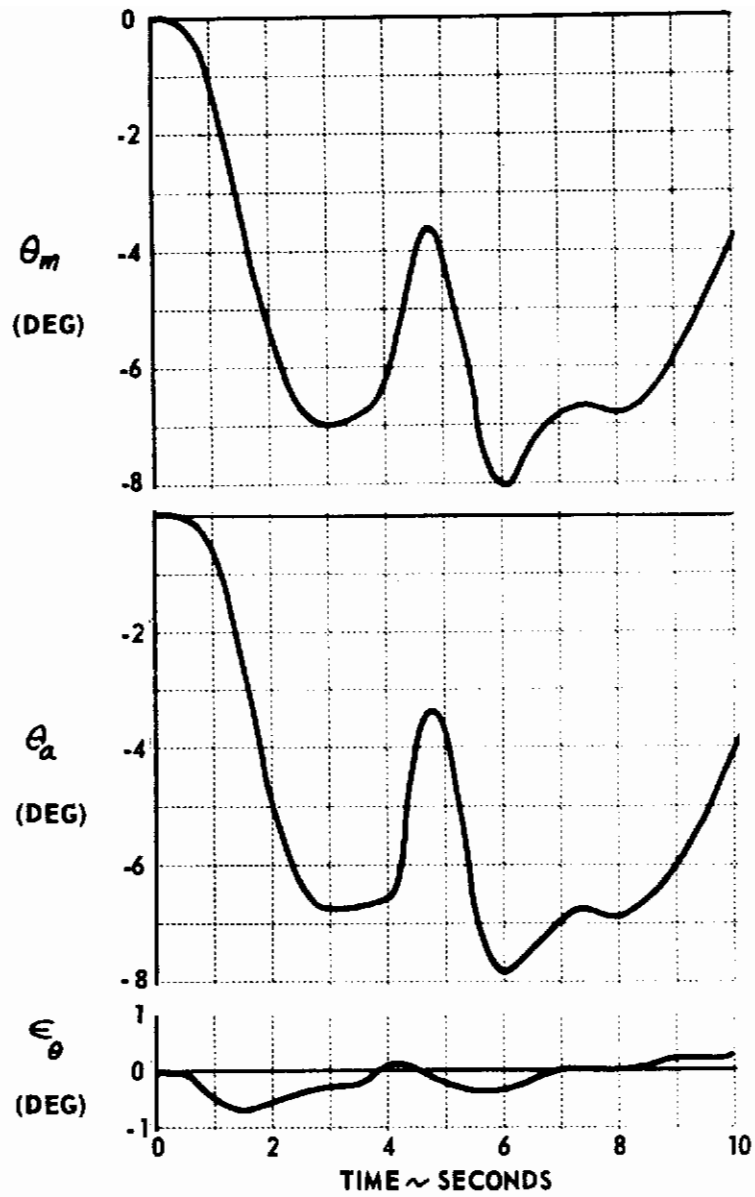


Figure 10 C-5A - MODEL-FOLLOWING CASE 6,  $\omega_{n_{sp}} = 1$  RAD/SEC FORCED RESPONSE INPUTS BY PILOT

# Contrails

movement of the elevator stick. The input for the responses shown in the second figure of each set is for an elevator doublet input that is made by the pilot. In the third figure of each set, the responses result from the pilot making control inputs as he desires. For the synthetic elevator step input, the difference between  $\theta_a$  and  $\theta_m$  is generally less than 0.1 degree, as seen in Figures 2, 5, and 8. The maximum errors that occur in response to an elevator doublet input approach 1.0 degree for very short periods of time, while the input is being made as shown in Figures 3, 6, and 9. After the input is made, the pitch angle error ( $\epsilon_\theta$ ) oscillates in magnitude in Figure 3, but recedes to a small value in Figures 6 and 9. In each of the three figures (3, 6, and 9), the general character of the airplane pitch-angle response is the same as the model pitch angle. The last figure of each set, Figures 4, 7, and 10, show response to the pilot's general inputs. In these figures, the error is noted to be quite small. This is true even at rather high-frequency input components, as shown in Figures 7 and 10. The accuracy with which  $\theta_a$  followed  $\theta_m$  is thus shown to be highly satisfactory.

To ascertain that the analog computer was correctly programmed, time histories were obtained from both analog and digital computer solutions of the equations of motion. These sets of time histories were compared and found to be in agreement. Due to the nature of the simulation, as already described, only the airplane pitch angle ( $\theta_a$ ) followed the model. A question arises relative to the accuracy with which other responses (such as angle of attack) were matched. The airplane could not be expected to follow the angle of attack of the C-5A model, because the B-26 lift curve slope ( $L_\alpha$ ) is twice that of the C-5A during the flight condition which was simulated. The steady state value of normal acceleration is correct (because  $n_{z_{ss}} = V/g \dot{\gamma}_{ss} = V/g \dot{\theta}_{ss}$  as  $\dot{\alpha}_{ss} = 0$ ), but, because the angle of attack is not matched during the transient, the transient values of  $n_z$  are not matched. These characteristics can be seen in Figure 11, in which it is noticed that the time required to attain a steady state  $n_z$  is very long as a result of the phugoid mode. From Figure 11, it is also noted that the pitch-angle match is excellent and that the speed changes are nearly identical. It is also noted that, for the same input, the B-26 undergoes a greater change in both flight path angle ( $\gamma$ ) and rate

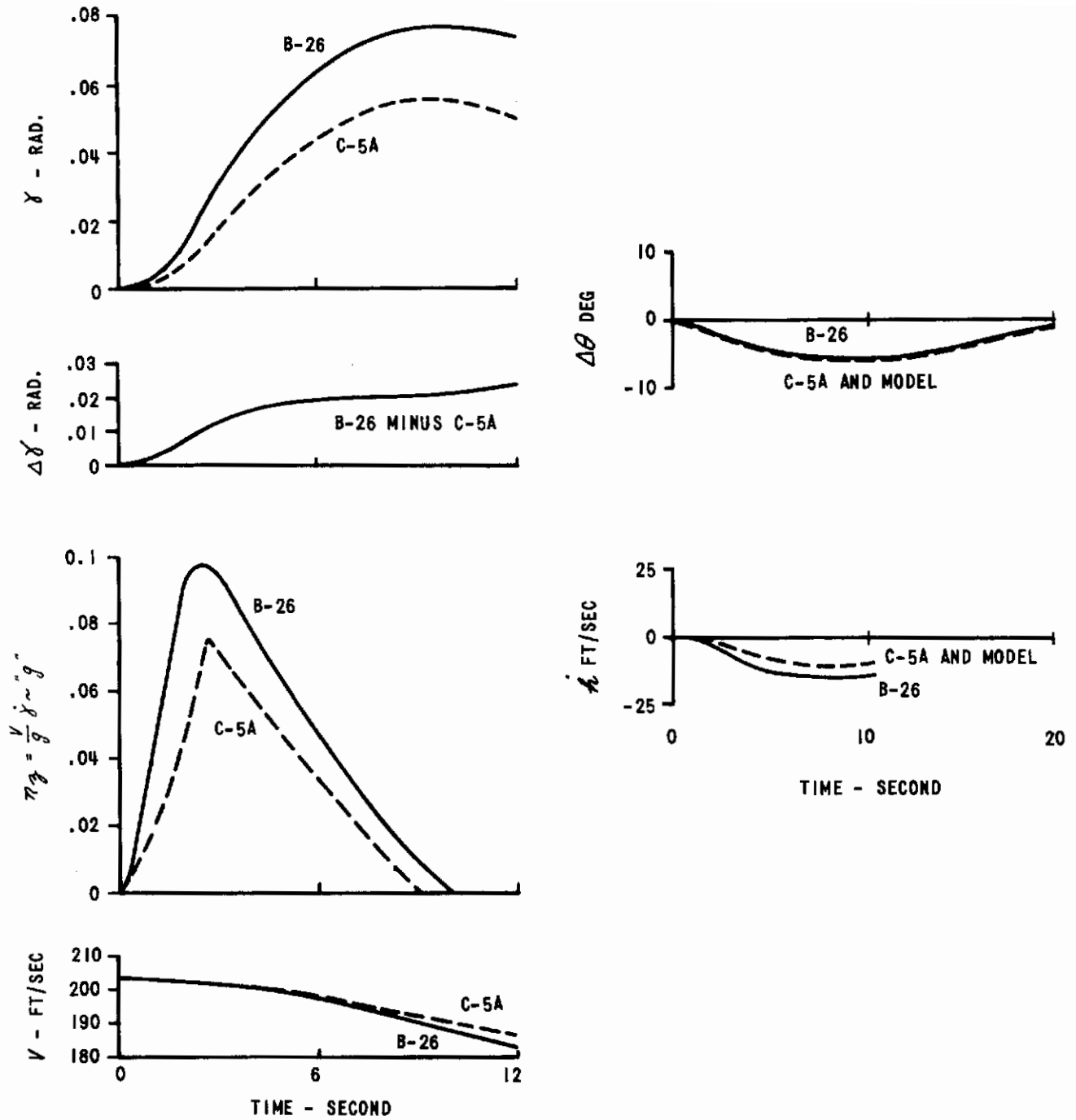


Figure 11 C-5A - PITCH-ANGLE MODEL-FOLLOWING ELEVATOR STEP RESPONSE  
 $L_{\alpha}$  OF MODEL =  $L_{\alpha}$  OF C-5A

# Contrails

of descent ( $\dot{h}$ ) than does the C-5A. Thus, the B-26 will flare somewhat more smartly than will the C-5A being simulated. In fact, the B-26 ballooned somewhat on the flare whenever the pilot did not exercise care and use a definite control technique to avoid the ballooning tendency. The tendency develops for another reason, also. The response of both simulated and actual C-5A is so slow that the pilot cannot properly judge the response from knowing the input. It is, therefore, very easy to overcontrol the initiation of the flare and any subsequent corrective inputs. Another contribution to the flare problem is that pitch-angle following allows the B-26 to respond according to its own value of  $L_\alpha$ , rather than the simulated  $L_\alpha$ , and this leads to mismatches of  $\delta$ ,  $\dot{h}$ , and transient  $n_z$ . No data exists which would justify ascribing all of the ballooning tendency to the mismatch in  $L_\alpha$ , without regard to the effect of slow response. Therefore, a conservative request was made of the pilots — that they give a rating of the ILS approach excluding the flare as well as a rating which included the flare. Such a procedure was followed because there is no known way to account for the difference in the flare characteristics.

The longitudinal equations of motion that were used on the analog computer are as follows:

$$\begin{aligned}\dot{V} &= -D_V \Delta V - D_\alpha \frac{\Delta \alpha}{57.3} - D_\theta \frac{\Delta \theta}{57.3} + D_{\delta_T} \Delta \delta_T \\ \dot{\alpha} &= \frac{\partial g}{\partial \dot{\alpha}} g + \frac{\partial \theta}{\partial \dot{\alpha}} \Delta \theta - 57.3 \frac{\partial \dot{V}}{\partial \dot{\alpha}} \dot{V} + \frac{57.3}{\partial \dot{\alpha}} \frac{g}{V_0} \Delta n_z \\ \Delta n_z &= \frac{V_0}{g} \left\{ \partial_V \Delta V + \partial_\alpha \frac{\Delta \alpha}{57.3} + \partial_{\delta_e} \frac{\Delta \delta_e}{57.3} \right\} \\ \dot{g} &= M_g g + M_\theta \Delta \theta + 57.3 M_V \dot{V} + 57.3 M_V \Delta V + \\ &\quad + M_{\dot{\alpha}} \dot{\alpha} + M_\alpha \Delta \alpha + M_{\delta_e} \Delta \delta_e\end{aligned}$$

# Contrails

The development of these equations is contained in Appendix I. The stability derivatives and constants that were used are as follows for the longitudinal case.

$$\begin{array}{lll}
 V_0 = 206 \text{ ft/sec} & \gamma_\alpha = -0.3875/\text{sec-rad} & D_\theta = 32.2 \frac{\text{ft/sec}^2}{\text{rad}} \\
 g = 32.2 \text{ ft/sec}^2 & \gamma_\theta = -0.0218 \text{ rad/sec} & D_{\delta_T} = 7.4 \frac{\text{ft/sec}^2}{\text{in.}} \\
 \alpha_0 = 0.139 \text{ rad} & D_\alpha = -16.5 \frac{\text{ft/sec}^2}{\text{rad}} & \gamma_\beta = \cos \alpha_0 = 0.98 \\
 \gamma_{\dot{V}} = \frac{\sin \alpha_0}{V_0} = 0.000674 & D_V = 0.051/\text{sec} & \gamma_{\dot{\alpha}} = \cos \alpha_0 = 0.98 \\
 \frac{\gamma_V}{V_0} = -0.00155 & \gamma_{\delta_e} = -0.0228 & \\
 \zeta_{SP} = 0.7 & M_q = -0.284 & 
 \end{array}$$

$f_{n_{sp}}$ cps	$M_\alpha$	$M_{\dot{\alpha}}$	$M_\theta$	$M_{\dot{V}}$	$M_V$	$M_{\delta_e}$
0.064	-0.0499	0.155	0.03531	0.00194	0.000391	-0.0835
0.10	-0.284	-0.165	0.0380	0.00099	0.000134	-0.2155
0.16	-0.972	-0.741	0.0195	-0.00222	-0.000705	-0.60

The stability derivatives supplied by the Air Force give an undamped short-period natural frequency of 0.13 cps and a damping ratio of 0.61.



## SECTION 3

### LATERAL-DIRECTIONAL SIMULATION

The response-feedback method of variable stability was used to simulate the lateral-directional characteristics of the C-5A. With this technique, the desired response characteristics were produced by making the lumped constants of the characteristic equation of the variable-stability airplane match the lumped constants of the characteristic equation of the C-5A. First, a description of the response-feedback technique of simulation is presented.

Although the response-feedback technique is older and better known than the model-following technique, the concept is more involved. The response-feedback technique is sensitive only to the responses of the airplane. The pilot's commands to the cockpit controls directly move the aerodynamic controls of the airplane. The airplane responds to the pilot's manipulation of the controls, and these airplane responses are fed back to computer circuitry which is a part of the variable-stability system; thus, the name, "response-feedback system." The computing circuitry operates on the feedback signals according to preset values of gain to obtain a set of signals which will operate the aerodynamic controls on the airplane in addition to (and separate from) the manipulations of the pilot. For example, if the pilot applies a rudder input, such as a step, the airplane responses are sensed by a sideslip vane and by attitude and rate gyros. If the sideslip response and the derivative  $N_{\beta}$  are considered, the operation of the response-feedback system can be visualized as follows.

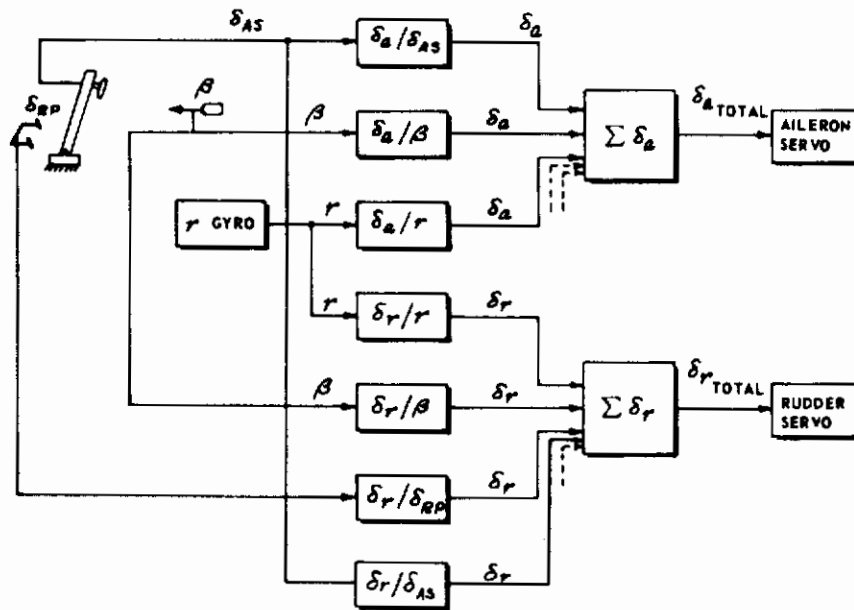
The sideslip response is sensed by the sideslip vane which generates a corresponding electrical signal. This signal is operated on by circuitry which can change both its sense and level. The modified sideslip signal is used to operate the rudder to either increase, decrease, or leave unaltered the sideslip response of the airplane. In this manner, the sideslip response can be made to appear as though the value of  $N_{\beta}$  had been changed from that of the basic B-26 to some other value. Although the pilot controls the aerodynamic surfaces directly, he does so through an electrohydraulic servo system which

# Contrails

does not feed the position of the aerodynamic control surface back to the pilot. Thus, the pilot is unaware of the motions of the aerodynamic controls that are caused by the additional signals from the simulation system.

This simulation system must be calibrated to determine the effects of each signal. Whenever a specific simulation is required, the calibration grids are consulted to determine what signal gains must be used. These gains are then checked in flight to determine if the desired dynamic characteristics have been achieved. Refinements to the gain settings are frequently required, and these additional calibration flights must then be made. The process continues until the desired accuracy is obtained. In the present program, the desired result was a matching of the Dutch-roll characteristics and matching of  $\tau_R$ , the roll mode time constant, and three values of  $(\frac{pb}{2u})_{max}$ . The spiral mode time constant was also to be matched; however, part way through the program the spiral was discovered to be twice as divergent as it was supposed to be. Time did not permit correction of the spiral for the remainder of the tests.

A partial block diagram of the response-feedback system is as follows:



In this figure, the gains that can be adjusted are:

- |                             |                             |
|-----------------------------|-----------------------------|
| 1. $\delta_a / \delta_{AS}$ | 4. $\delta_r / \delta_{RP}$ |
| 2. $\delta_a / \beta$       | 5. $\delta_r / \beta$       |
| 3. $\delta_a / r$           | 6. $\delta_r / r$           |

Additional signals to those shown exist in the B-26, but the above sketch is indicative of the response-feedback simulation system.

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In most conventional aircraft, the cockpit control-system force and displacement gradients are supplied independently by the feedback of forces from the aerodynamic controls. However, in the variable-stability B-26, an electrohydraulic servomechanism is used to provide the force and displacement feel for the elevator stick. Springs are used to provide the force feel for the aileron wheel, and a torsion bar is used for the force feel of the rudder pedals. The artificial feel systems make it possible to give the pilot various magnitudes of control-force gradients.

For this program, a lag was introduced to simulate the time required to displace the lateral controls. With this lag, sudden full aileron wheel deflection produces an essentially ramp type of aileron deflection which reaches maximum displacement in 0.6 second. Figure 12 illustrates the circuit which produces this lag, and the response of this system to a step command is shown in Figure 13. The lag circuit includes both acceleration and rate limiting, and it represents a second-order system with an undamped natural frequency of 2.23 cps and a damping ratio of 0.7. Due to the acceleration and rate limiting, the lag is proportional to the size of the aileron wheel input. A response of this lag system to a pilot ramp input of full aileron wheel is shown in Figure 14. This latter response is more typical of what will generally occur in flight because pilots are unable to make true step inputs.

To determine the accuracy of the lateral-directional simulation, flight calibration records were obtained and analyzed, and time histories were computed on a digital computer and compared with the flight recorded time histories. The characteristics that were determined from flight records are given in Table I, while comparisons of computed and recorded time histories are shown in Figures 15 through 19. The responses to aileron inputs that are shown in Figures 15 through 17 include the simulated aileron lag in both the calculated and recorded responses. The responses to rudder inputs, shown in Figures 18 and 19, are to rudder doublet inputs. The responses were computed after the flight time histories were obtained so that the input determined from the flight record could be used for the computed responses. Figures 18 and 19 illustrate that the spiral is more divergent in the flight records than it is in the computed responses. The flight response has a different mean line than does the computed response.

# Contrails

Figure 18 shows a time to double amplitude of the spiral mode of 6 to 7 seconds. This is rather consistent with other flight measurements which yielded times to double amplitudes of 8 to 10 seconds. In general, the spiral time constant is difficult to determine, because it is very difficult to obtain a pure spiral response.

The maximum value of  $\frac{pb}{2u}$  (based on C-5A dimensions) versus  $\phi$  obtained in one second (with the aileron lag operative) is shown in Figure 20.  $p_{max}$  is defined as shown in the inset of the figure. This value for maximum  $p$  differs from that which would be computed for a first-order roll mode, because the Dutch roll is included in the flight time history response. The yaw due to aileron was slightly adverse to zero in the simulation. It is noted in Figure 20 that neither the desired value of  $\left(\frac{pb}{2u}\right)_{max} = 0.3$  nor a roll angle of 8 degrees in one second was obtained. The roll rate data ( $p$ ) presented in this report are obtained by matching the  $\int p dt$  with bank angle,  $\phi$ . This is done because reason was found, after the program was completed, to suspect the roll rate gyro data.

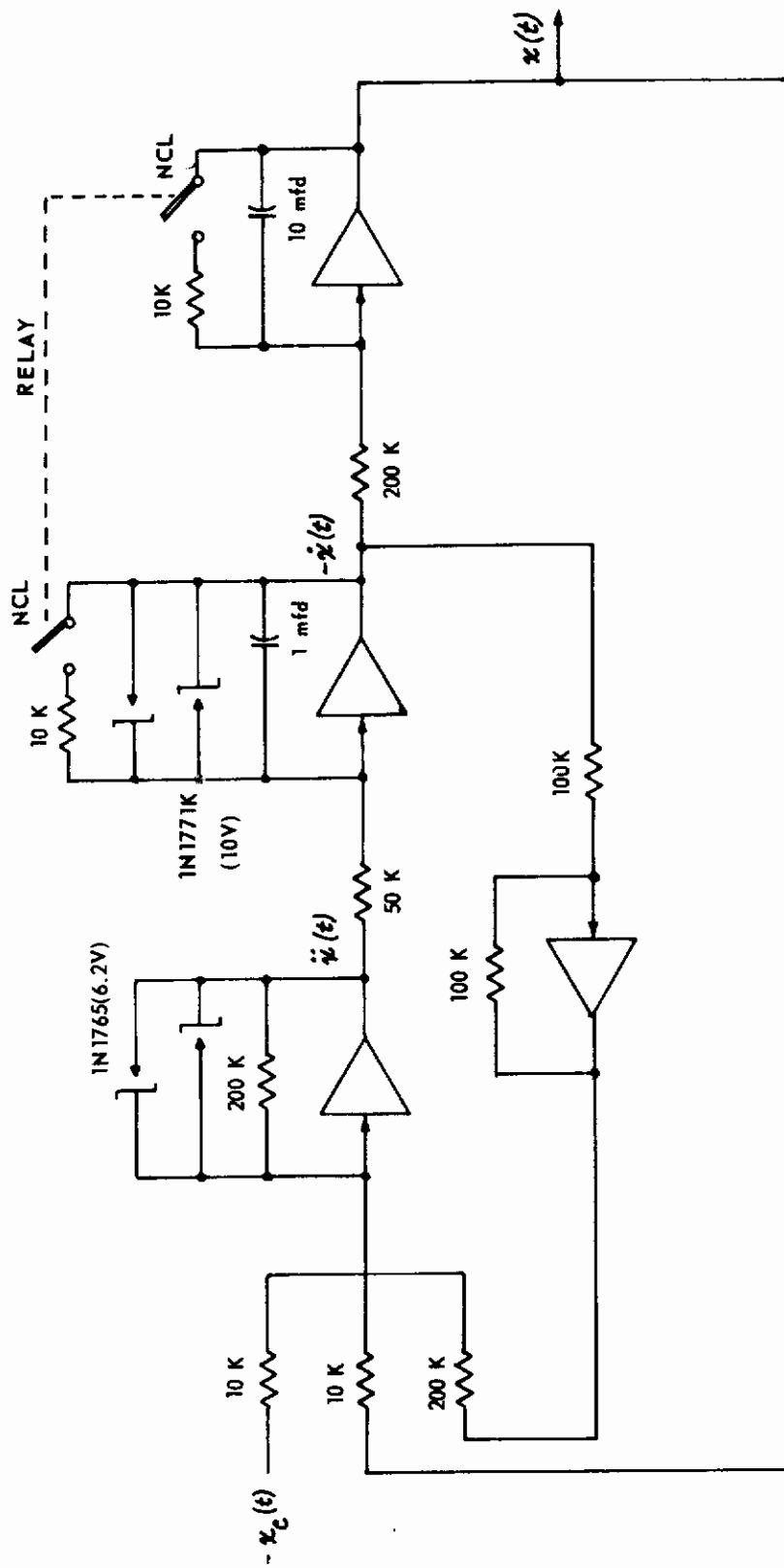


Figure 12 AILERON LAG CIRCUIT

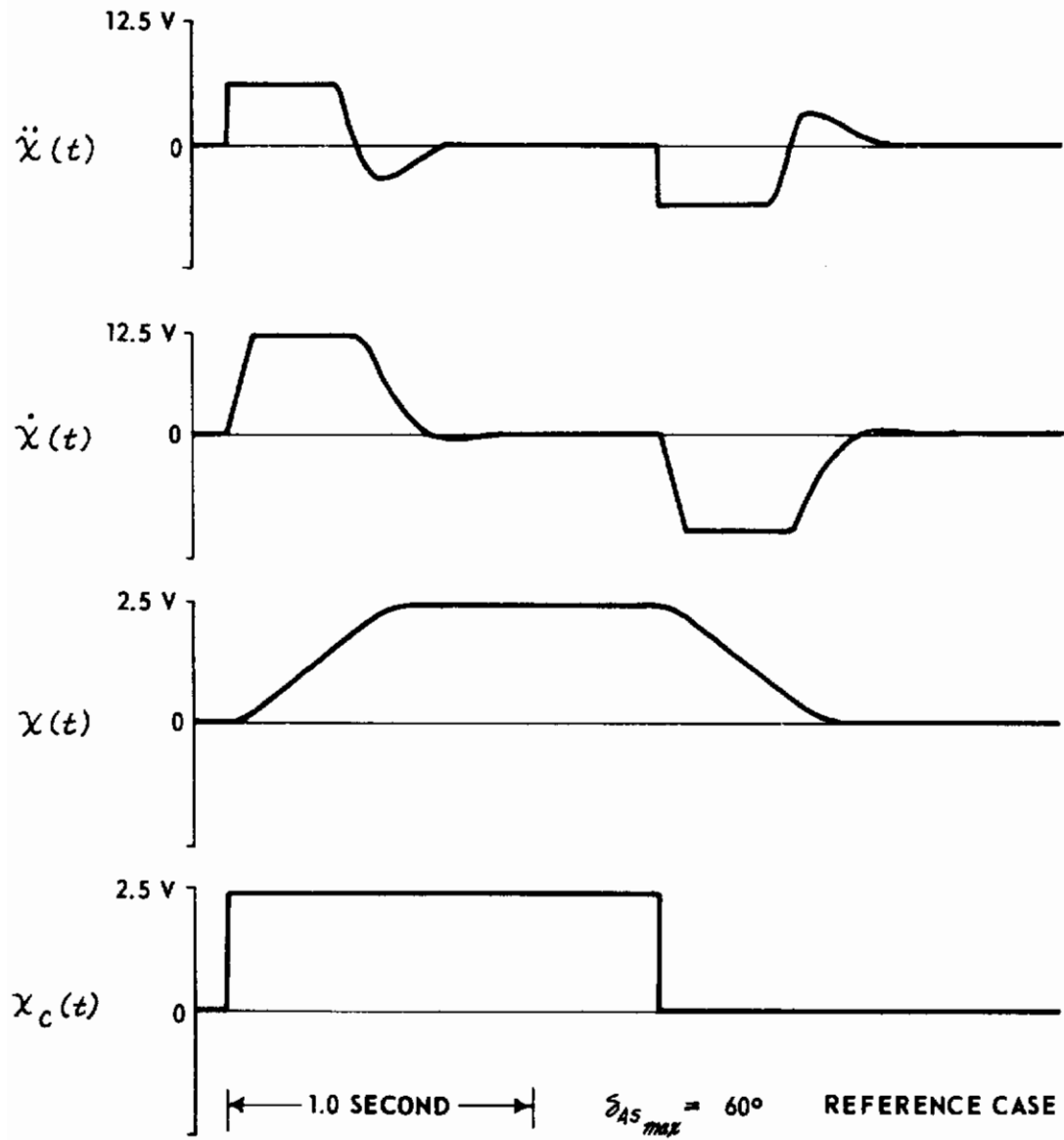


Figure 13 ANALOG RESPONSES OF AILERON LAG SYSTEM

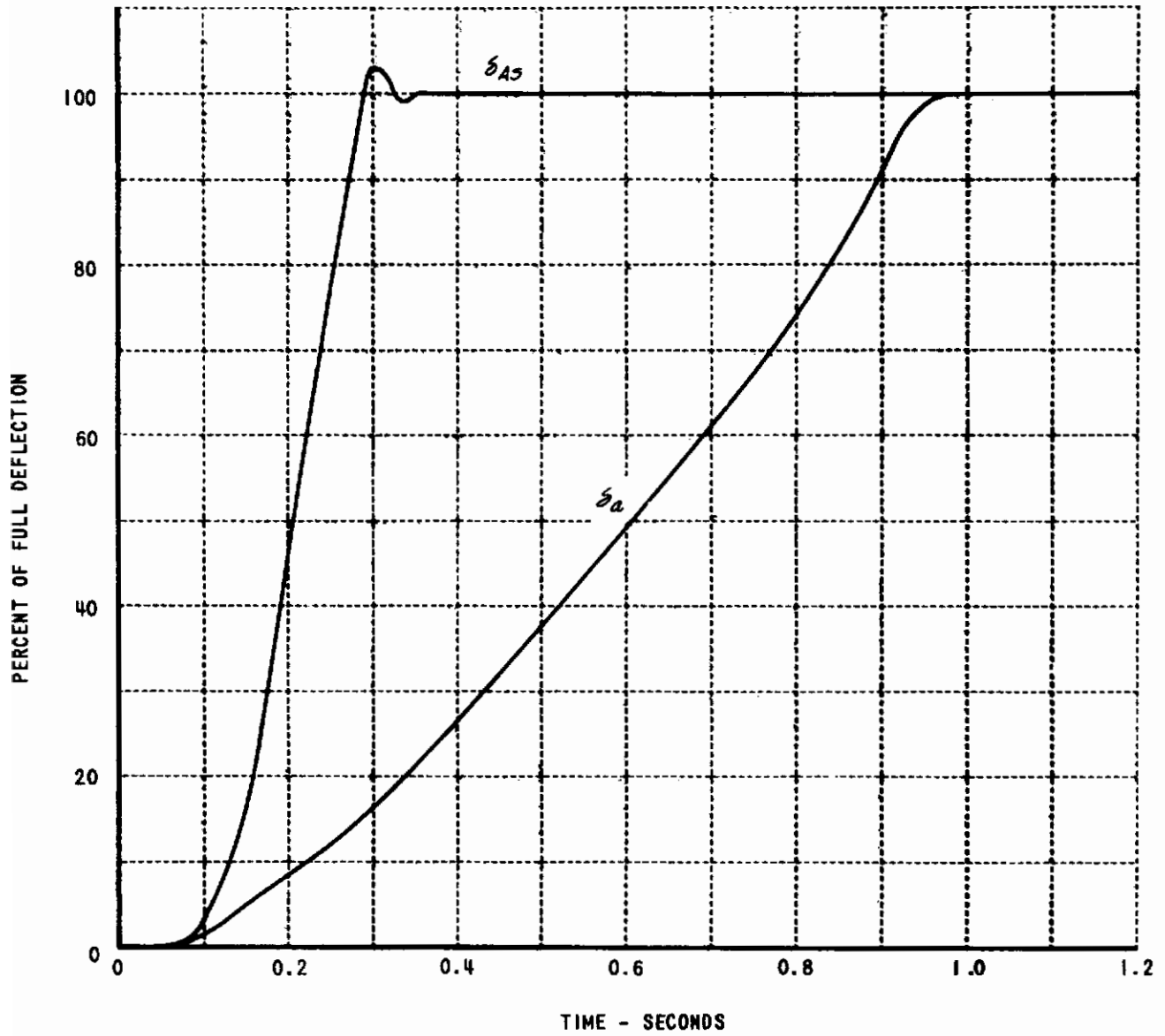


Figure 14 B-26 AILERON SERVO LAG DURING C-5A SIMULATION

TABLE I  
C-5A DYNAMICS, CALCULATED AND SIMULATED

PARAMETER	CALCULATED	MATCHED IN FLIGHT		
		$\tau_R = 1.4$	$\tau_R = 1.0$	$\tau_R = .6$
$\zeta_d$	= .1578	.16	.16	.13
$\omega_{nd}$	= .757 RAD/SEC			
$\omega_d$	= .7475 RAD/SEC			
$f$	= .119 C/S			
$T$	= 8.4 SEC	8.37	8.6	8.5
$\tau_R$	= 1.1 SEC	1.38	1.0	.62
$\tau_S$	= 32.6 SEC			
TIME TO DOUBLE $T_{2s}$	= 22.5 SEC	8-10 SEC	8-10 SEC	8-10 SEC
$ \phi/B $	= 1.22	1.3	1.3	1.0
$\chi(\phi/B)$	= 68 DEG	92 DEG	84 DEG	89 DEG
$\zeta_\phi$	= .274			
$\omega_\phi/\omega_d$	= .739			
		RECORD 19 DR RECORD 21 $\tau_R$ FLT. 1007	RECORD 16 DR RECORD 18 $\tau_R$ FLT. 1007	RECORD 27 DR RECORD 28 $\tau_R$ FLT. 1011



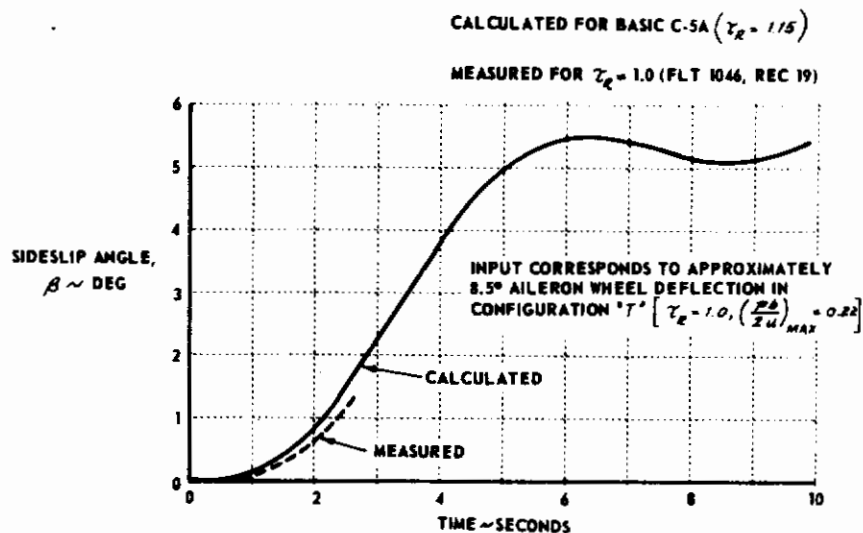


Figure 15 SIDESLIP RESPONSE TO AILERON INPUT\*

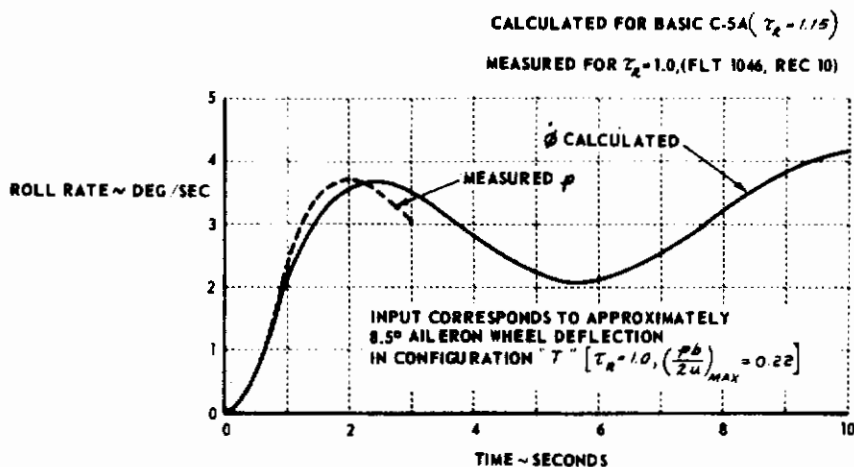
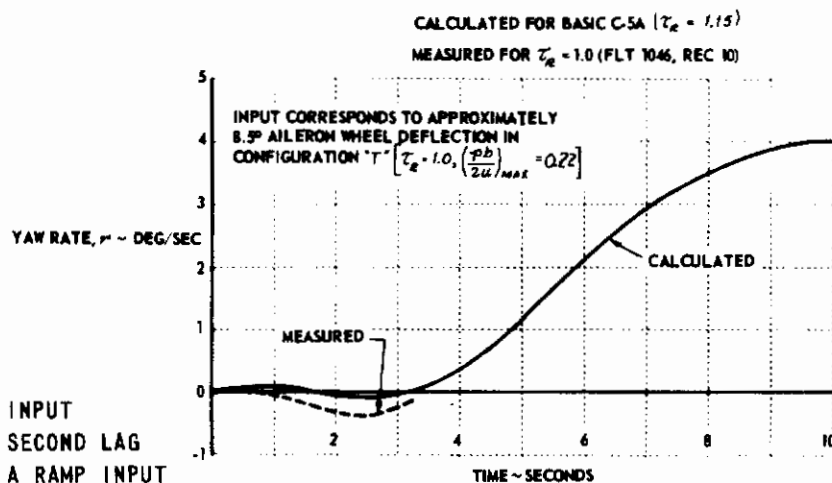


Figure 16 ROLL RATE RESPONSE TO AILERON INPUT\*



\* EACH AILERON INPUT INCLUDES 0.8 SECOND LAG RESULTING IN A RAMP INPUT

Figure 17 YAW RATE RESPONSE TO AILERON INPUT\*

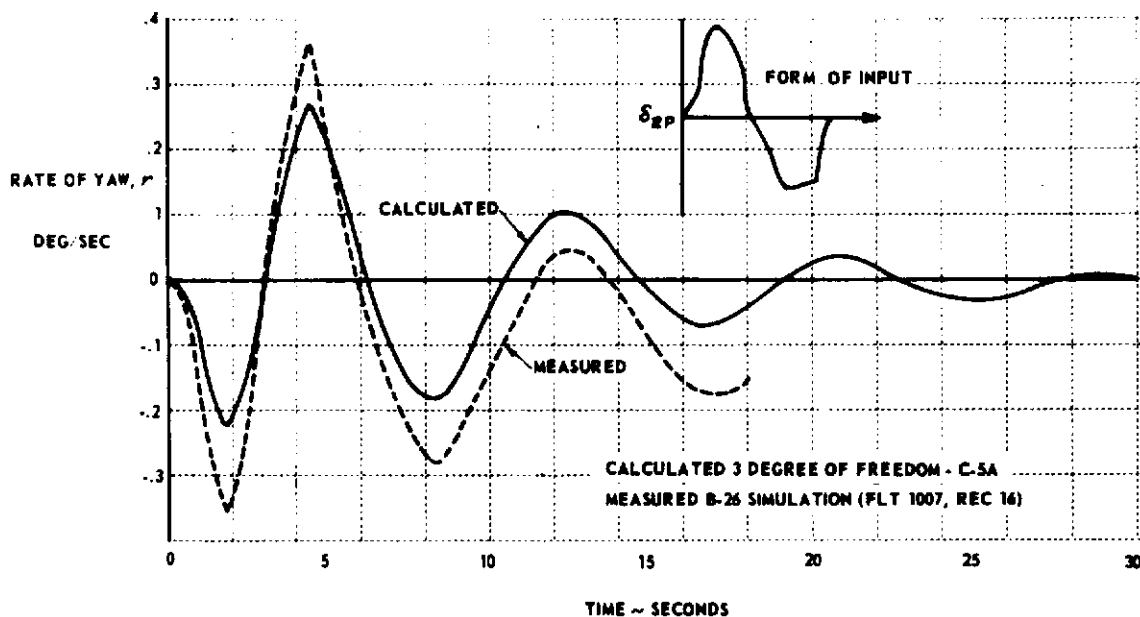


Figure 18 YAW RATE RESPONSE TO RUDDER DOUBLET

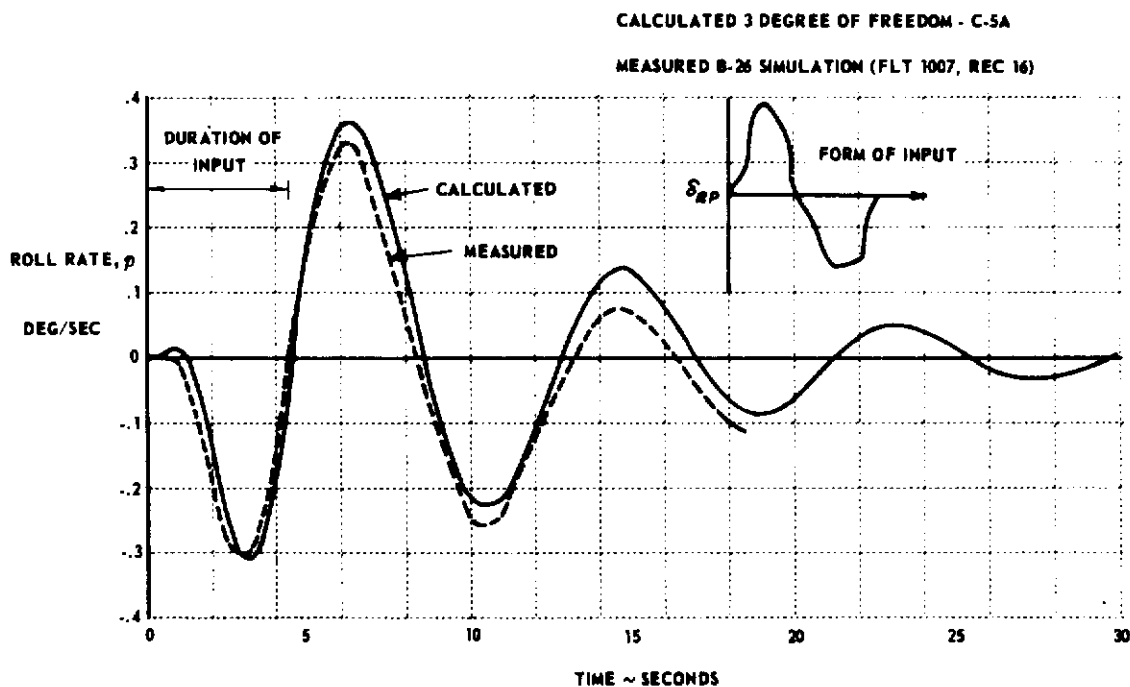


Figure 19 ROLL RATE RESPONSE TO RUDDER DOUBLET

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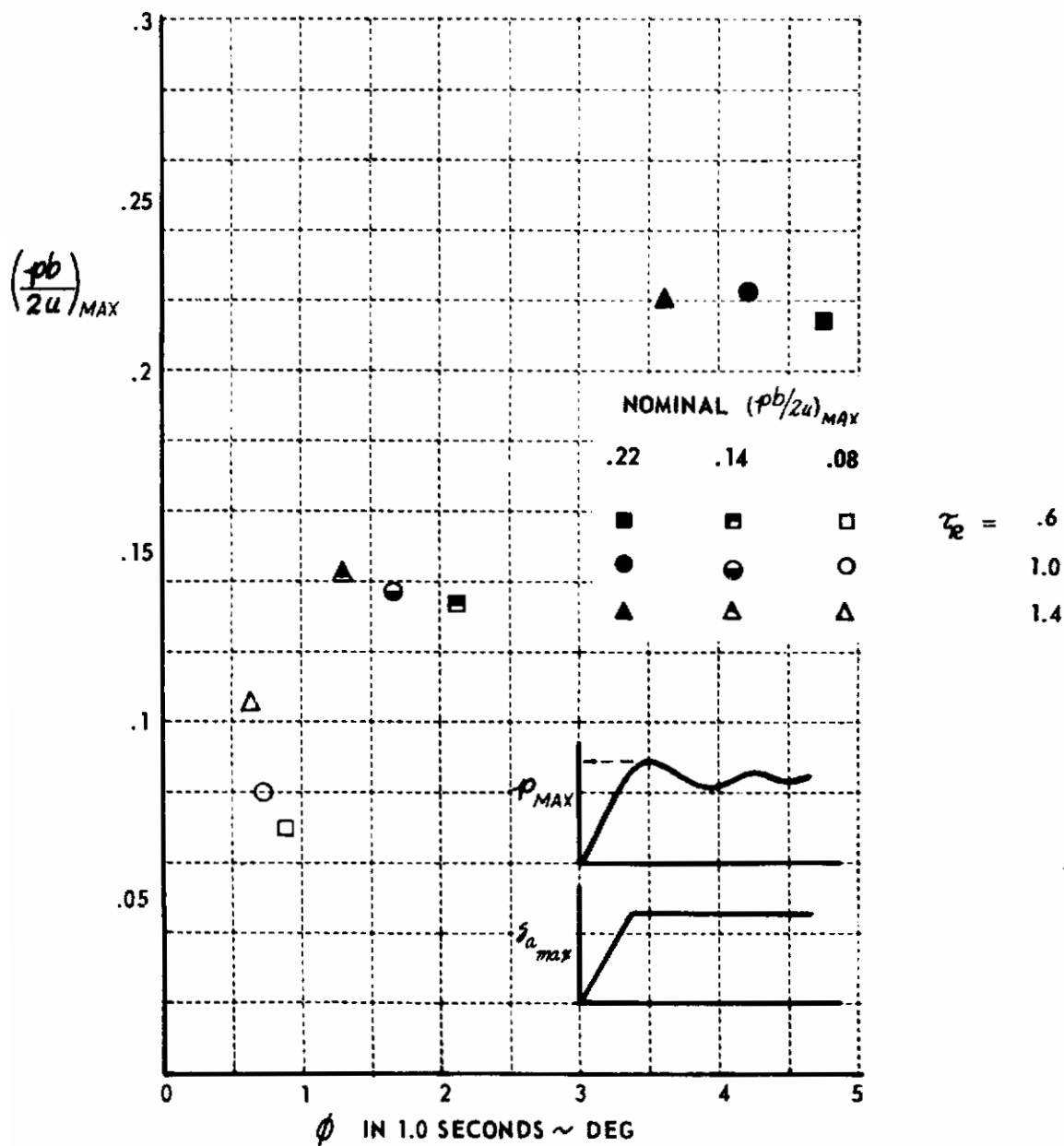


Figure 20  $p_{MAX}$  FOR  $\delta_a$  STEP INPUT, LAG IS IN

## SECTION 4 THE EXPERIMENT

Five pilots participated in the evaluation program. One pilot was made available by each of the following organizations: Cornell Aeronautical Laboratory, Air Force Flight Test Center, Boeing (Seattle), Douglas, and Lockheed (Georgia).

The evaluation task for this program was an ILS approach to 200 feet breakout and then continuation as a VFR approach to low altitude at the airfield. The evaluation pilot flew under the hood for some time prior to intercepting the outer marker. He went under the hood while on a dogleg outside the outer marker and approximately 1000 feet above outer-marker intercept altitude. Thus, the pilot began the ILS approach by having to reduce his altitude and to acquire the localizer prior to glide slope interception at the outer marker. From the outer marker inbound, he performed a standard ILS approach down to 200 feet above runway altitude. At the 200-foot point, he removed the hood and proceeded VFR to the airfield and a very low approach. The approach was carried sufficiently low that the pilot had to initiate a flare, and, in some instances, the flare was continued to touchdown or almost to touchdown.

Each pilot made at least two (sometimes three) consecutive approaches for each configuration that was evaluated. Generally, the evaluation pilot first flew a new configuration in up-and-away VFR flight to feel out the response characteristics of the configuration. Sometimes, this initial familiarization was performed both VFR and IFR. The first ILS pass was then accomplished normally, with the pilot attempting to make a good approach and visual flare. The second ILS pass was often performed with an intentional lateral offset with respect to centerline so that, at breakout at 200 feet, the pilot had to make an S-turn to line up with the runway. This maneuver was used so that the pilot could evaluate the effects of having to maneuver the airplane rather rapidly. Also, often during the second ILS, the pilot purposely put a wing down and then tried to pick it up rapidly to observe the effect of this maneuver on his ability to perform the ILS task. This helped

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the pilot to evaluate how the airplane would respond to control if the wing had gone down as the result of a gust. If a third pass was made, it was usually initiated relatively close in, and was a VFR approach to allow the pilot to more fully observe the flare characteristics of the airplane.

The pilots were not informed of the dynamic characteristics which were to be evaluated. Rather, all configurations were referred to only by a code letter.

As discussed earlier, the simulated flare in the B-26 does not exactly match the flare that the C-5A will have, and, therefore, the pilots considered only the very initial round out of the flare in their evaluations for the majority of the data. Some of the initial evaluations include a considerable portion of the flare in the overall rating of the configuration, and this usually made the rating worse than it would otherwise have been, because the flare was so difficult to do smoothly.

The pilots further noted that sideslip was very difficult to control, and that the sideslip produced in turn entry and recovery was more than they were accustomed to seeing. Computations using the C-5A stability derivatives showed sideslip response characteristics very close to the characteristics observed in the flight simulation. Therefore, the sideslip control problem that was presented in the simulation was realistic and representative of the unaugmented C-5A for the set of stability derivatives upon which the simulation was based.

One longitudinal configuration was used during all of the lateral-directional tests, and this is noted as the base configuration in the data tables of Appendix II.

For all of the longitudinal runs of pilot A, the lateral-directional configuration was P. For the evaluations of one pass with the longitudinal configuration D by pilot B, the lateral configuration was P. Pilot C evaluated longitudinal configurations D, F, and H with lateral configuration P. For the remainder of the evaluations by pilots B and C, the base lateral-directional configuration was T, which has a value for  $\left(\frac{\rho b}{2u}\right)_{max}$  of 0.22, whereas configuration P had a value for  $\left(\frac{\rho b}{2u}\right)_{max}$  of 0.14 (see Table III). These values of  $\frac{\rho b}{2u}$  are based on

C-5A dimensions. The lateral-directional base configuration for all runs of pilots D and E was configuration T.

In all cases, the pilots rated the longitudinal configurations independently of the base lateral-directional configuration. They also rated the lateral-directional configurations independently of the longitudinal base configuration. Their comments indicate that they are confident in their ability to separate the modes.

For each evaluation run, the pilots were given a comment card to help them organize their comments and also to prevent their forgetting some pertinent information. In general, they would give free-style comments first, and, then, they would use the cards for further comments. The pilots were encouraged to give their comments in simple, straightforward language rather than in technical terms. It is more important that the pilot carefully and accurately define his observations and impressions than it is that he attempts to ascertain the technical causes for his impressions and observations. His observations will always be valid, but very often his technical analysis may be incorrect. This is a result of being able, in some instances, to obtain similar pilot observations with two technically different situations. The comment cards used by the pilots are reproduced below.

## C-5A COMMENT CHECK LIST

### LONGITUDINAL

Ease and precision of making small angular correction  
Technique?  
Tendency to PIO?

Stability - Does airplane stay at given pitch angle and  
airspeed?

Trim well defined? Does longitudinal response affect  
ability to locate trim?

Trim sensitivity

Response to throttle - Is it realistic?

# Contrails

Turns - Does nose drop in turns?  
Do you note anything unusual in pitch attitude  
in a turn?

Forces - Level of force  
Gradient  
Friction  
Suitability

Stick travel - Suitability?

## LATERAL

Ease of initiating turn  
Ease of stopping turn on heading  
Technique  
Roll authority

Start lateral roll correction

Stop lateral roll correction

Change heading

Pick up wing

Lag - time to respond

Tendency to overshoot and oscillate

What control is used?

What instrument is used?

### C-5A - TASK - ILS Down to 200', Plus Flare

Ability to hold altitude (straight and level, in turns)

Technique: Elevator  
Throttle  
Elevator and throttle  
Trim

Why: What is aggravating? What is good?

Ability to establish rate of descent (straight and level, in turns)

How do you do it?

Why this way?

What aggravates?

What is good?

Ability to hold rate of descent ( straight and level, in turns)

Technique:  $d_e$   
 $T$   
 $d_e$  and  $T$   
Trim

Why:           What aggravates?           What is good?

Ability to hold heading

Prior to localizer intercept  
    What instruments used for intercept?  
    Trim  
On localizer ( straight and level and during descent)  
    Trim

Are you rushed for time anywhere during approach?

Where?       Why?

Do you tend to oscillate the airplane in:

- a) Altitude
- b) Attitude
- c) Heading
- d) Airspeed

How do you stop an oscillation?

How do you flare the airplane?

Where do you initial flare?           Why?  
Does the flare require different technique or different  
    emphasis of technique?

How?                                   Why?

Do you misjudge the flare?           How?

The pilot's verbal comments were made and recorded in flight immediately. This procedure insured that the pilot's observations and impressions were obtained while they were still fresh in his mind. Pilot comments and pilot ratings constitute the data for the analysis. In some instances, the rating was not stated in the recorded comments. However, an observer on board the airplane kept a record of all ratings given, and some of the pilot's ratings are taken from the observer's record.



## CAL TEN-POINT RATING SCALE FOR AIRPLANE FLYING QUALITIES

The ten-point scale as developed and used at Cornell Aeronautical Laboratory to rate airplane flying qualities is shown below. The CAL scale is a general rating scale which is used to evaluate the suitability of a configuration for performing a specific task or mission.

CAL Ten-Point Rating Scale

Category	Adjective Description Within Category	Numerical Rating
Acceptable	Excellent	1
and	Good	2
Satisfactory	Fair	3
Acceptable	Fair	4
but	Poor	5
Unsatisfactory	Bad	6
Unacceptable	Bad*	7
	Very Bad**	8
	Dangerous <sup>+</sup>	9
Unflyable	Unflyable	10

\* requires major portion of pilot's attention  
\*\* controllable only with a minimum of cockpit duties  
+ aircraft just controllable with complete attention

The ratings were tabulated, and the mean rating for each configuration was obtained.

The comments were read carefully for important and pertinent statements concerning the characteristics of each configuration, the manner in which they influence the pilot, and what he does. These statements are tabulated in summarized form in Tables IV through X in Appendix II where the gross trends in the pilot's comments can be seen easily. Further summarization of the comments leads to the gross-trend statements that are included on Figures 21 and 22 in Section 5.

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The sequence of configurations was the same for each pilot and is the same as the alphabetical sequence given in Tables II and III in Section 5. All of the longitudinal configurations were rated first, and then the lateral-directional configurations were rated.

In evaluating the airplane, the pilot considered the important response mode of the airplane as it affected him in performing the ILS landing approach task. The pilot must do this because he can not separate the individual effects of, say, short-period frequency or damping ratio from the effects of other parameters. For example, the effects of short-period frequency and stick-force per g are so intermingled that a change of the value of one can lead the pilot to conclude that the other has been changed. Therefore, it is important to realize that the pilot evaluates the entire complex as he sees it. Furthermore, the results from this study are applicable only to the ILS landing task and not to the entire flight envelope of the C-5A.

The control force and motion characteristics used in the simulation are as follows:

## Longitudinal

$$F_{Es}/g = 100 \frac{lb}{g} \text{ and } 60 \frac{lb}{g}$$
$$\delta_{Es}/g = 8 \frac{in.}{g} \text{ and } 2 \frac{in.}{g}$$

## Lateral-directional

$$\delta_{AS} = \pm 60^\circ$$
$$F_{AS} = \pm 24 \text{ lb at full throw}$$
$$F_{RP}/\delta_{RP} = 82 \text{ lb/in.}$$

## SECTION 5

### RESULTS

The results of the longitudinal and lateral-directional investigations are discussed separately.

#### LONGITUDINAL EVALUATION

Table II presents the results of the longitudinal evaluation in terms of the average pilot rating, the range of pilot rating, and the standard deviation of the rating for each configuration. These terms are defined in Appendix II. From the range and standard deviation, it is noted that the pilots were in consistent agreement except, perhaps, for configuration H (see Figure 21). From past experience, it is considered that the pilots in this experiment are essentially as consistent among themselves as a larger sample of pilots would be expected to be.

The results of the longitudinal investigation indicate the following trends of pilot acceptance of the different modal characteristics.

- a. The short-period frequencies of 0.16 cps and 0.10 cps both have overall average ratings of 4.83 to show that these frequencies are better liked than the lower frequency of 0.064 cps for which the overall average rating is 6.43.
- b. There is a weak trend in favor of the  $100 \frac{\text{lb}}{\text{g}}$  stick force for the landing maneuver for which the overall average rating is 5.12; the  $60 \frac{\text{lb}}{\text{g}}$  stick force overall average rating is 5.82.
- c. The larger stick motion of  $8 \frac{\text{in.}}{\text{g}}$ , for which the overall average rating is 4.85, is liked more than the  $2 \frac{\text{in.}}{\text{g}}$  stick motion gradient, for which the overall average rating is 6.4.
- d. The configurations with  $100 \frac{\text{lb}}{\text{g}}$  stick force gradient and  $8 \frac{\text{in.}}{\text{g}}$  stick motion gradient (overall average rating 4.4) are preferred over the configurations which have  $60 \frac{\text{lb}}{\text{g}}$  with  $8 \frac{\text{in.}}{\text{g}}$  (overall average rating 5.30), and over the configurations with  $100 \frac{\text{lb}}{\text{g}}$

TABLE II  
RESULTS OF LONGITUDINAL EVALUATIONS

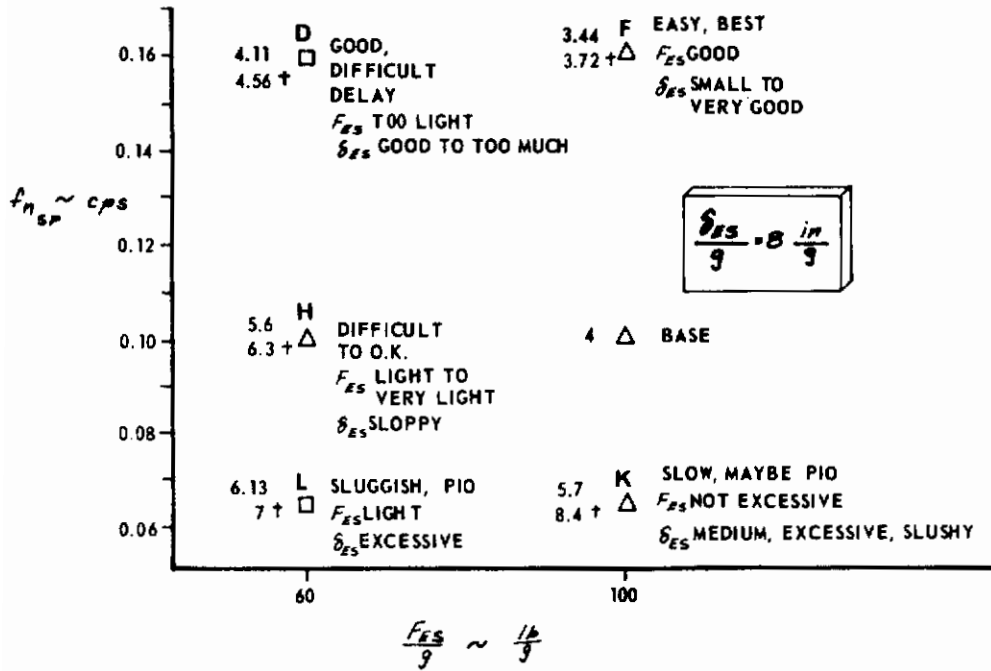
CONFIG	LONGITUDINAL CHARACTERISTICS							PILOT EVALUATIONS			
	$f_{nsP}$ cps	$\sum_{sp}$	$F_{Es/g}$ lb/g	$\delta_{ES/g}$ in./g	$F_{ES/g}$ lb/in.	$f_{hp}$ cps	$\sum_p$	$\bar{R}$	$R_N$	$S_R$	$n$
D	0.16	0.7	60	8	7.5	0.03	0.05	4.11	2	0.89	9
F	0.16		100	8	12.5			3.44	2	0.75	9
H	0.10		60	8	12.5			5.66	6	2.16	6
I	0.064		60	2	30			7.4	1	0.548	5
J	0.16		60	2	30			5.8	3	1.34	6
K	0.064		100	8	12.5			5.7	4	1.47	5
L	0.064		60	8	7.5			6.13	11/2	0.517	4
Q	0.064		100	2	50			6.5	31/2	1.64	6
S	0.16		100	2	50			5.9	21/2	1.15	5
BASE	0.10		100	8	12.5			4	4	1.5	7

$\bar{R}$  ~ AVERAGE PILOT RATING  
 $R_N$  ~ RANGE OF PILOT RATING  
 $S_R$  ~ STANDARD DEVIATION OF PILOT RATING

$$= \sqrt{\frac{n}{n-1} \left[ \frac{\sum R^2}{n} - \left( \frac{\sum R}{n} \right)^2 \right]}$$

WHERE n = NO. OF RATINGS

# Contrails



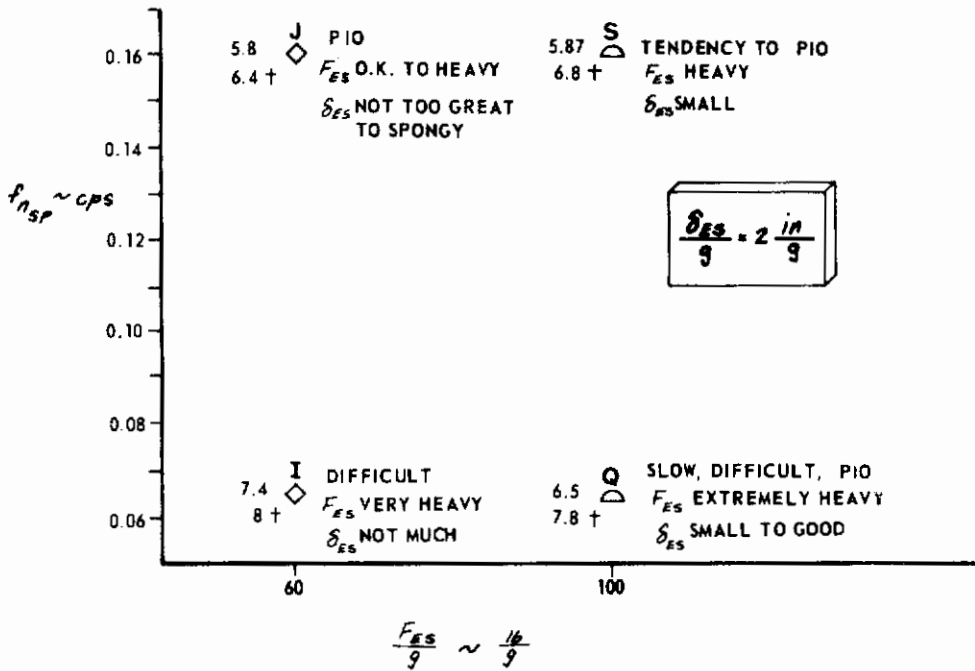
$f_{n_{sp}}$  vs  $\frac{F_{ES}}{g}$

FOR  $\frac{F_{ES}}{g}$  AND  $\frac{\delta_{ES}}{g}$  VARIED

$\zeta_{SP} = \text{CONSTANT} = 0.7$

$f_{n_p} = 0.03 \text{ CPS}$      $\zeta_p = 0.05$

$\frac{F_{ES}}{\delta_{ES}} \sim \frac{lb}{in}$	SYMBOL
7.5	□
12.5	△
30.	◇
50.	◐



THE AVERAGE RATINGS NEGLECT THE FLARE RATING

† AVERAGE RATINGS INCLUDING FLARE

Figure 21 C-5A CAL B-26 17H PILOT EVALUATIONS 5 PILOTS AVERAGE RATINGS AND REMARKS 26 MAY 1965

# Conclusions

and  $2 \frac{\text{in.}}{\text{g}}$  (overall average rating 6.2), and over the configurations with  $60 \frac{\text{lb}}{\text{g}}$  and  $2 \frac{\text{in.}}{\text{g}}$  (overall average rating 6.6). The implication here is that the lowest stick sensitivity in terms of both force and motion gradients is best liked of the combinations investigated; that is, the combined gradients of  $100 \frac{\text{lb}}{\text{g}}$  and  $8 \frac{\text{in.}}{\text{g}}$ , which can be expressed as sensitivities of  $0.01 \frac{\text{g}}{\text{lb}}$  and  $0.125 \frac{\text{g}}{\text{in.}}$ , is the best combination.

The fact that a higher stick force per g is liked at lower speed than at higher speeds is established in Reference 3, where there is a definite relationship between desired stick force per g and airspeed. The task described in Reference 3 was that of an attack bomber rather than a landing approach. Nevertheless, the data of Reference 3 show a preference for  $50 \frac{\text{lb}}{\text{g}}$  at 220 knots,  $60 \frac{\text{lb}}{\text{g}}$  at 175 knots, and  $75 \frac{\text{lb}}{\text{g}}$  at 130 knots. Although the pilots in this program did not state their reasons for choosing the higher stick force per g, there are reasons that can be cited for this preference as discussed in Reference 4 and as noticed during stability and control demonstrations to the classes of test pilot students at the Navy Test Pilot School at Patuxent River, Maryland. These reasons are set forth here as a possible explanation for the choice of the higher stick force per g. At too low a stick force gradient, the pilot's body motions, during turbulence, become definite control inputs; the stick feel is not as definite around trim and makes accurate trimming of the airplane more difficult; and the pilot cannot discern speed changes through stick force changes as well as he can with heavier forces. The heavier forces on approach are not too disconcerting, because the pilot will, at most, pull relatively small amounts of g and will therefore apply only a small amount of stick force. With heavier forces, the pilot can feel the small inputs he makes around trim conditions, and he can better feel speed changes through force changes at constant attitude. Also, with higher forces, the pilot's inadvertent inputs result in smaller airplane responses. At approach speeds, the airplane is not as maneuverable, in terms of g that can be pulled, and, furthermore, the pilot is not interested in curving the flight path very strongly or in pulling all the available g. Therefore, the pilot can afford to accept (and seems to prefer) higher stick force per g for the landing maneuver. At higher speeds, the airplane is more maneuverable, and the pilot who wishes to use this maneu-

verability will want lighter stick force gradients but still not so light that he can inadvertently overstress the airplane.

In the results of the present experiment, the trend of pilot preference for a  $100 \frac{\text{lb}}{\text{g}}$  stick force gradient over a  $60 \frac{\text{lb}}{\text{g}}$  gradient is weak.

The apparent trend in the data is stronger with stick motion per g in that the pilots prefer  $8 \frac{\text{in.}}{\text{g}}$  (overall average rating 4.85) to  $2 \frac{\text{in.}}{\text{g}}$  (rating 6.4). The most preferred configuration of those tested is for a combination of  $100 \frac{\text{lb}}{\text{g}}$  force gradient and an  $8 \frac{\text{in.}}{\text{g}}$  motion gradient at 0.16 cps short-period undamped natural frequency. Apparently, for this configuration, the overall "harmony of control" is best. Note that, for the stick motion gradient of  $2 \frac{\text{in.}}{\text{g}}$ , the force gradient of  $60 \frac{\text{lb}}{\text{g}}$  is "O. K. to heavy" to "very heavy," and  $100 \frac{\text{lb}}{\text{g}}$  gradient is "heavy" to "excessively heavy." There is a rating interaction among the short-period undamped natural frequency, the stick motion gradient, and the stick force gradient. Except for configuration I, the ratings all tend to be in the acceptable to unsatisfactory region.

The best configuration tested was configuration F for which the undamped short-period natural frequency was 0.16 cps (the highest evaluated), the stick force gradient was  $100 \frac{\text{lb}}{\text{g}}$ , and the stick motion gradient was  $8 \frac{\text{in.}}{\text{g}}$ . (During these evaluations, the short period damping ratio was held constant at 0.7; the phugoid characteristics, also constant, were  $f_{np} = 0.03$  cps and  $\zeta_p = 0.05$ .)

## LATERAL-DIRECTIONAL EVALUATION

The lateral-directional investigation was performed with configurations in which values of the roll mode time constant,  $\tau_R$ , and the maximum roll rate expressed as  $\left(\frac{pb}{2u}\right)_{max}$  were different from one configuration to another. Three values of the roll-mode time constant were used: 0.6, 1.0, and 1.4 seconds. The nominal values obtained for  $\left(\frac{pb}{2u}\right)_{max}$  were 0.22, 0.14; and 0.08 and are shown in Figure 20. The aileron wheel was stopped at  $\pm 60^\circ$  throws (as this is typical of the proposed throws for the C-5A), and the force for full throw of the wheel was 24 pounds. The simulated aileron lag was in use throughout the evaluations and, with the pilot's imperfect step input and the servo system lags, yields an effective lag of around 0.8 second for full aileron deflection. This is shown in Figure 14 which is a record of an in-flight attempt by the pilot to make a step aileron input. The

same longitudinal configuration, denoted "base for lateral-directional," was used throughout the lateral-directional evaluations to provide the pilot with a constant set of appropriate longitudinal dynamics. These dynamics are summarized in Table II.

The results of the lateral-directional investigation and the definitions of the configurations are given in Table III. From this table, it is seen that the values for the range and the standard deviation are small and consistent, which means that the pilots were in general agreement. These data, along with summarized pilot comments, are presented in Figure 22, which is a plot of average pilot rating on a  $\left(\frac{pb}{2u}\right)_{max}$  versus  $\tau_R$  field.

At  $\left(\frac{pb}{2u}\right)_{max} = 0.22$ , the ratings are nearly invariant with  $\tau_R$ , the roll power is adequate to good, and the total aileron lag does not seem large. The fact that the roll power was adequate to good does not mean that it was excellent in all respects, because there were times when the wing was down that the pilot used full aileron to bring the wing up. During pilots B and C evaluations of the longitudinal configurations, the base lateral-directional configuration was changed from P to T. Both pilots felt that the change from  $\left(\frac{pb}{2u}\right)_{max} = 0.14$  (for P) to 0.22 (for T) was no strong improvement. Both of these configurations have a  $\tau_R$  of 1.0. Both pilots were informed of the change of the lateral-directional configuration. Pilot B said of the comparison:

"The modified lateral characteristics are just barely usable for this type of turbulence (winds 18 knots gusting to 30 - I would call it not particularly heavy, but choppy turbulence - it's moderate). Although there is considerably more roll power available. It's still very marginal in that full control is used frequently and both hands are required on the wheel to properly control the airplane; but, I agree, (it) will be usable for this work."

Pilot C says of the comparison of the two lateral-directional configurations:

"Well, on the first run, I tried turns on final and I still had the same complaints. It might, I don't know, it might have been modified somewhat, but I still had trouble making small, precise heading corrections, and it was still difficult for me to enter a turn and roll out on a desired heading. - Laterally, I think it's still a little slow on response."



TABLE III  
RESULTS OF LATERAL-DIRECTIONAL EVALUATION

CONF.	LATERAL CHARACTERISTICS					PILOT EVALUATIONS			
	$\tau_R$ sec	$\frac{pb}{2u_{MAX}}$	$f_d$ cps	$\zeta_d$	$T_{25}$ sec	$\bar{R}$	$R_N$	$S_R$	$n$
N	0.6	0.22	0.12	0.16	8-10	4.4	2	0.895	5
O	1.4	0.105				8.9	2	0.75	5
P	1.0	0.14				6.88	2	0.8	4
R	0.6	0.07				7.63	2	1.075	4
T	1.0	0.22				4.5	1	0.57	4
U	1.4	0.22				4.1	2	0.75	5
V	1.4	0.14				7.1	3	1.25	5
W	1.0	0.08				8.5	1	0.51	5
X	0.6	0.135				5.80	2 1/2	0.91	5

$\bar{R}$  ~ AVERAGE PILOT RATING  
 $R_N$  ~ RANGE OF PILOT RATING  
 $S_R$  ~ STANDARD DEVIATION OF PILOT RATING

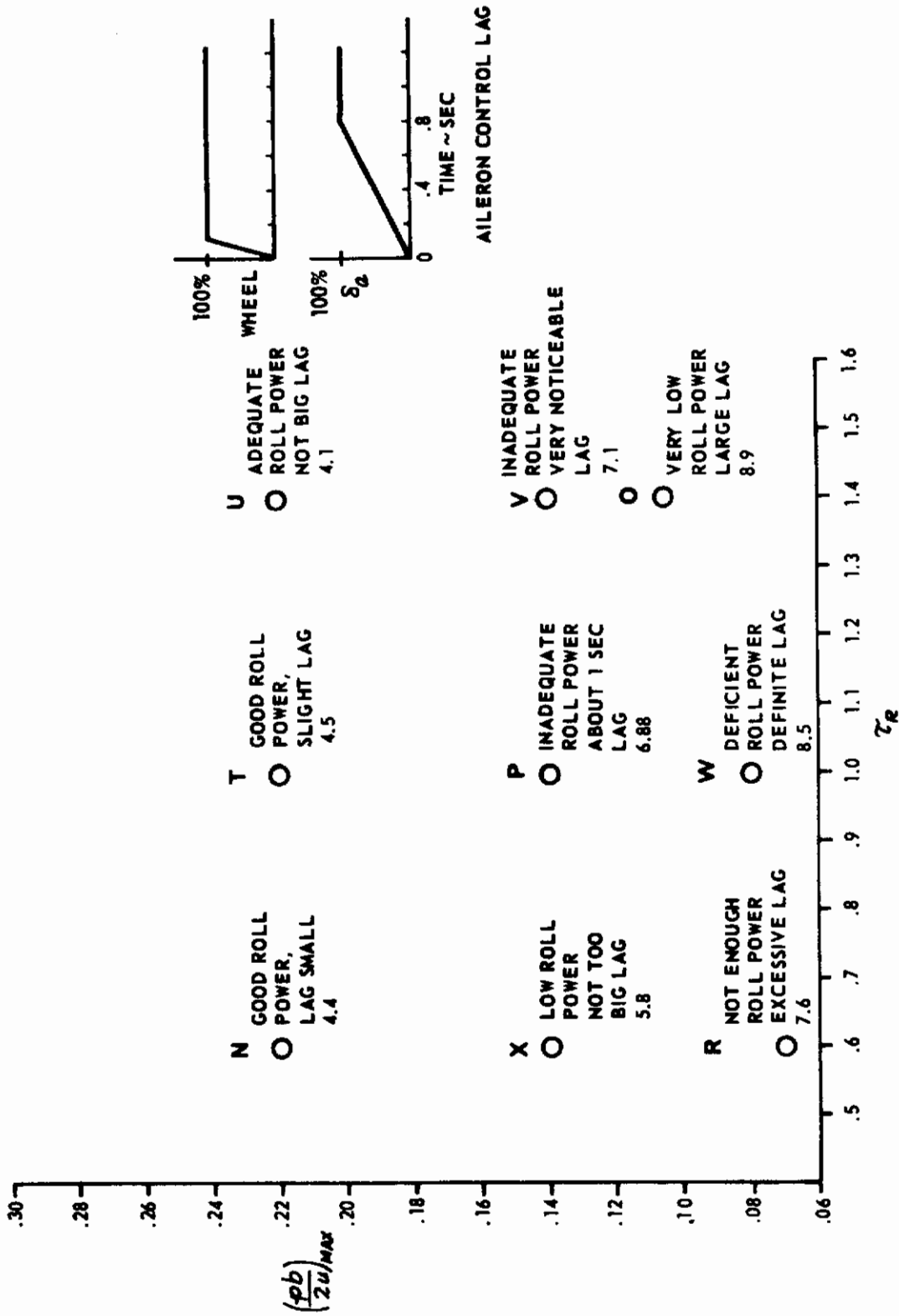


Figure 22 C-5A CAL B-26 17H PILOT EVALUATION 5 PILOTS AVERAGE RATINGS AND REMARKS 25 MAY 1965

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One pilot definitely notices a change in roll power between the configurations but feels that the better one is very marginal, and the other pilot is not convinced that there is much of a difference between the configurations. These comments indicate that, whenever the roll power is called good to adequate, it is not free from criticism. The remainder of the dynamics and especially the ability to start and stop yaw rate is poor, and this may be affecting the pilot's opinions.

At the  $\left(\frac{pb}{2u}\right)_{max}$  of 0.22, there is no degradation of pilot rating as  $\tau_R$  increases. Generally, for fighter-type aircraft in which IFR tasks are performed, there is a degradation in rating as  $\tau_R$  increases beyond 0.5 to 0.6 as shown in References 5 and 6, because the roll damping becomes insufficient for precise control of bank angle. One would expect an even stronger trend of degradation with increasing  $\tau_R$  in this experiment because of the combined aileron lag and  $\tau_R$ . Perhaps this trend does not occur because of the considerably divergent spiral mode which caused all the pilots to remark that they have difficulty in maintaining a heading angle. In addition to the effects of the spiral mode on the ability of the pilot to hold heading, it is seen from Figure 17 that it takes yaw rate approximately three seconds to respond after an aileron input has been made and that, if the pilot wants yaw immediately, he will then have to use the rudder. Some of the pilots remarked that they use the rudder a great deal in an attempt to maintain or correct heading. The suggestion, then, is that the heading problems outweigh, or mask, the expected trend with  $\tau_R$ . There also are no data to allow a distinct and separate effect of the simulated aileron lag to be determined.

At a  $\left(\frac{pb}{2u}\right)_{max}$  of 0.14, the roll power is low and inadequate, the effect of the combined aileron lag and  $\tau_R$  is to degrade the ratings as  $\tau_R$  is increased, and the combined lag is noticeable. The pilots complained about their inability to maintain a heading; again, this is due to the unstable spiral mode and the long time it takes to get a yaw rate started with an aileron input as seen in the first portion of the response shown in Figure 17. Since these characteristics were constant throughout, there are no data to show trends with changes in the spiral and yaw characteristics. The trend of

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ratings with  $\tau_R$  is no stronger than would normally be expected, and, therefore, there is no specific trend that can be ascribed directly to the aileron lag.

For a  $\left(\frac{pb}{2u}\right)_{max}$  of 0.08, there is simply not sufficient roll power, and the aileron lag appears to be very large. Again, the trend of ratings with  $\tau_R$  is not unexpected, but the trend is not emphatic enough to ascribe to it effects of the aileron lag. With this roll power, the pilots frequently have to use full aileron and still do not obtain a reasonable roll rate.

On the basis of comparing overall averages, the average rating for the configurations with a  $\left(\frac{pb}{2u}\right)_{max}$  of 0.14 is 6.59, and, for the lowest  $\left(\frac{pb}{2u}\right)_{max}$ , the average rating is 8.3. Clearly,  $\left(\frac{pb}{2u}\right)_{max} = 0.22$  is better liked.

The trend of average ratings with  $\tau_R$  is 5.93 at  $\tau_R = 0.6$ , 6.63 at  $\tau_R = 1.0$ , and 6.7 at  $\tau_R = 1.4$ . There is, therefore, no strong trend of rating with  $\tau_R$ . All of the ratings given are as if the airplane were unaugmented. If characteristics had been flown which represented a stability augmented airplane, much better characteristics would have been evaluated and much better ratings would have been obtained.

## SECTION 6 CONCLUSIONS

### LONGITUDINAL

1. An  $f_{n_{SP}} = 0.16$  cps is preferred over lower frequencies at a  $\xi_{SP} = 0.7$ , particularly when  $\delta_{ES}/g = 8$  in./g as compared to  $\delta_{ES}/g = 2$  in./g.
2.  $\delta_{ES}/g = 8$  in./g is preferred to  $\delta_{ES}/g = 2$  in./g.
3. For  $\delta_{ES}/g = 8$  in./g, the value of  $F_{ES}/g = 100$  lb/g is preferred, slightly, over  $F_{ES}/g = 60$  lb/g.
4. All conclusions are restricted to the landing approach, which is the only flight condition which was investigated.
5. With control force and control motion gradients optimized, the ratings were in the "acceptable but unsatisfactory" band. At the highest short-period frequency, the ratings were close to the "acceptable and satisfactory" boundary, and, at the lowest frequency, the ratings were close to the "unacceptable" boundary.
6. Ratings during the flare maneuver are not necessarily applicable to the C-5A due to limitations of the simulation equipment for this maneuver.

### LATERAL-DIRECTIONAL

1. For the largest  $\left(\frac{pb}{2u}\right)_{max} = 0.22$ , the roll power is adequate, although not excellent, and the aileron lag is considered small.
2. For  $\left(\frac{pb}{2u}\right)_{max} = 0.14$ , the roll power is low and the effects of the aileron lag are noticeable.

# Conclusions

3. For  $\left(\frac{pb}{2u}\right)_{max} = 0.08$ , the roll power is very low and the aileron lag is large to excessive.
4. It is possible that the simulated mechanical lag in the aileron response has very little degrading influence at the several  $\left(\frac{pb}{2u}\right)_{max}$  conditions. The degradation shown correlates with the higher values of  $\tau_R$ .
5. The evidence of these tests indicates that adequate lateral control can be achieved with a bank angle during the first second less than 8 degrees. The greatest value of this quantity which was used during these tests was 4.75 degrees, and lateral control was judged to be adequate with  $\phi_1$  as low as 3.5 degrees.
6. The basic lateral-directional dynamics of the unaugmented airplane were such that the highest mean rating achieved was approximately 4. It is probable that more favorable ratings would have been achieved at the various lateral control configurations had augmented lateral-directional dynamic characteristics been simulated.
7. Roll power in terms of peak  $\frac{pb}{2u}$  of 0.22 is adequate as is a  $\phi_1$  of between 3.5 and 4.5 degrees. A roll power of 0.14 is low to inadequate and leads to a  $\phi_1$  of 2 degrees. These remarks are for the aileron lag operative and a full aileron input.
8. It is suspected that the improper spiral mode in this simulation caused lower pilot ratings than would have been obtained with the proper spiral mode time constant.

## GENERAL

1. The consistency of the pilot ratings was good, and their comments correlated well with the dynamic characteristics which they evaluated.

## APPENDIX I

### DEVELOPMENT OF C-5A MODEL-FOLLOWING SIMULATION EQUATIONS (LONGITUDINAL)

The three-degree-of-freedom longitudinal equations of motion, which were used to represent the C-5A longitudinally, were linearized perturbation expressions about non-orthogonal axes. The "drag equation" or "x-force equation" was written along the flight path or wind axis. The z-force equation was the perturbation form of the z-body axis equation, while the pitching moment equation was written with reference to the y-body axis. Since perturbation expressions about trim conditions are used, the y- and z-body axes can be considered as stability axes in their normal definition. Hence, the aerodynamic coefficients in the z-force and pitching moment expressions are composed of the common stability derivatives referred to as stability axes. The wind axis was used for the drag equation, because total acceleration and total velocity are explicit variables. The drag equations contain total force coefficients.

The concept of the C-5A simulation was that of flying a model-following B-26 variable-stability aircraft so that a defined evaluation task was performed. The mathematical model was formed by programming the computer to solve the linearized perturbation longitudinal equations, which described the C-5A. Thus, the model computed the longitudinal dynamics of the C-5A in response to normal pilot inputs of elevator column, pitch trim, and throttle about the trim conditions which existed when the model-following system was engaged. Therefore, the flight conditions when the model-following system was engaged needed to be the same as those mathematically included in the coefficients of the equations. Close scrutiny, however, showed that some deviations produced negligible errors.

Linearization of the equations was included to reduce analog equipment requirements and checkout time. Certain small-angle approximations were made to simplify computation.

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Reference 7 details the development of both longitudinal and lateral equations for the non-orthogonal axis system, starting with total force and moment expressions through change to the perturbation format (subtracting out trim terms) and ending with the linearization of these perturbation expressions with respect to small changes in the variables about the trim (or engage) conditions.

Expanding the associated equations, one obtains (neglecting all terms involving lateral-directional variables):

Drag Equation:

$$(S + D_V) \Delta V + D_\alpha \Delta \alpha + D_\theta \Delta \theta = D_{\delta_e} \Delta \delta_e + D_{\delta_T} \Delta \delta_T$$

Z-Force Equation:

$$\begin{aligned} & \left( \frac{\cos \beta_0 \sin \alpha_0}{V_0} s - z_V \right) \Delta V + (\cos \beta_0 \cos \alpha_0 s - z_\alpha) \Delta \alpha \\ & + \left( -\sec \phi_0 \left[ \sin \beta_0 \sin \phi_0 \tan \theta_0 + \cos \alpha_0 \cos \beta_0 \right] s - z_\theta \right) \Delta \theta \\ & = z'_{\delta_e} \Delta \delta_e + z_{\delta_T} \Delta \delta_T \end{aligned}$$

Pitching Moment Equation:

$$\begin{aligned} & -m_V \Delta V - (m_{\dot{\alpha}} s + m_\alpha) \Delta \alpha + (\sec \phi_0 s^2 - m_\theta \sec \phi_0 s) \Delta \theta \\ & = m_{\delta_e} \Delta \delta_e + m_{\delta_T} \Delta \delta_T \end{aligned}$$

The thrust was assumed to act through the center of gravity and along the flight path with negligible component along the z-body axis. The trim (engage) condition also specified that  $\beta_0 = \phi_0 = 0$ .

Hence, the equations reduce to:

$$\begin{aligned} & (S + D_V) \Delta V + D_\alpha \Delta \alpha + D_\theta \Delta \theta = D_{\delta_e} \Delta \delta_e + D_{\delta_T} \Delta \delta_T \\ & \left( \frac{\sin \alpha_0 s}{V_0} - z_V \right) \Delta V + (\cos \alpha_0 s - z_\alpha) \Delta \alpha - (\cos \alpha_0 s + z_\theta) \Delta \theta \\ & \qquad \qquad \qquad = z'_{\delta_e} \Delta \delta_e \\ & -m_V \Delta V - (m_{\dot{\alpha}} s + m_\alpha) \Delta \alpha + (s^2 - m_\theta s) \Delta \theta = m_{\delta_e} \Delta \delta_e \end{aligned}$$



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For ease of computation, the approximations of  $\sin \alpha_0 = \alpha_0(\text{rad})$ ,  $\cos \alpha_0 = 1$  were made since  $\alpha_0$  was specified as +8 degrees. These assumptions are used to reduce the z-force equation to

$$\left(\frac{\alpha_0 s}{V_0} - z_v\right) \Delta V + (s - z_\alpha) \Delta \alpha - (s + z_\theta) \Delta \theta = z_{\delta_e} \Delta \delta_e$$

Note that, thus far, all angles are in radians.

Digital solutions of these equations with the coefficients computed from aerodynamic data supplied by the Air Force showed that variation of certain parameters affected both the short-period characteristics and the phugoid characteristics. For the purposes of the experiment, it was decided to maintain phugoid frequency and damping ratio constant for the various short-period combinations. Hence, an analysis was made to devise a synthetic technique to fulfill this requirement. It was found that addition of the terms  $m_{\dot{v}} \dot{v}$  and  $m_\theta \Delta \theta$  into the existing pitching moment equations produced the required results. Thus, the pitching moment equation was rewritten as:

$$-(m_{\dot{v}} s + m_v) \Delta V - (m_{\dot{\alpha}} s + m_\alpha) \Delta \alpha + (s^2 - m_\beta s - m_\theta) \Delta \theta = m_{\delta_e} \Delta \delta_e$$

Since practical in-flight measurement and display (if any) of angles is in degrees, the angular variables in the equations were defined in dimension of degrees and converted to radians for use in the mechanized equations. This operation results in the following equations:

$$(s + D_v) \Delta V + D_\alpha \frac{\Delta \alpha}{57.3} + D_\theta \frac{\Delta \theta}{57.3} = D_{\delta_e} \frac{\Delta \delta_e}{57.3} + D_{\delta_r} \Delta \delta_r$$

$$(z_{\dot{v}} s - z_v) \Delta V + (z_{\dot{\alpha}} s - z_\alpha) \frac{\Delta \alpha}{57.3} - (z_\beta s + z_\theta) \frac{\Delta \theta}{57.3} = z_{\delta_e} \frac{\Delta \delta_e}{57.3}$$

$$-(m_{\dot{v}} s + m_v) \Delta V - (m_{\dot{\alpha}} s + m_\alpha) \frac{\Delta \alpha}{57.3} + (s^2 - m_\beta s - m_\theta) \frac{\Delta \theta}{57.3} = m_{\delta_e} \frac{\Delta \delta_e}{57.3}$$

$D_{\delta_e}$  for the C-5A was considered negligible and hence deleted. Rewriting the z-force equation in terms of  $n_z$ , the normal acceleration, and rearranging a few terms gives the final equations in the form mechanized on the computer as follows:

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$$\dot{V} = -D_V \Delta V - D_\alpha \frac{\Delta \alpha}{57.3} - D_\theta \frac{\Delta \theta}{57.3} + D_{\delta_T} \Delta \delta_T$$

$$\ddot{\alpha} = \frac{\partial \dot{q}}{\partial \dot{\alpha}} \dot{q} + \frac{\partial \dot{\theta}}{\partial \dot{\alpha}} \Delta \theta - 57.3 \frac{\partial \dot{V}}{\partial \dot{\alpha}} \dot{V} + \frac{57.3}{\partial \dot{\alpha}} \frac{g}{V_0} \Delta n_3$$

$$\text{where } \Delta n_3 = \frac{V_0}{g} \left\{ \partial_V \Delta V + \partial_\alpha \frac{\Delta \alpha}{57.3} + \partial_{\delta_e} \frac{\Delta \delta_e}{57.3} \right\}$$

$$\begin{aligned} \dot{q} &= m_f \dot{q} + m_\theta \Delta \theta + 57.3 m_V \dot{V} + 57.3 m_V \Delta V \\ &\quad + m_{\dot{\alpha}} \dot{\alpha} + m_\alpha \Delta \alpha + m_{\delta_e} \Delta \delta_e \end{aligned}$$

where  $S \Delta V = \dot{V}$ ,  $\dot{V}_0$  (at engage) = 0, and  $\dot{V} = \dot{V}_0 + \Delta \dot{V}$

similarly  $S^2 \Delta \theta = \dot{q}$ ,  $\dot{q}_0 = 0$

$$S \Delta \theta = q, \quad q_0 = 0$$

$$S \Delta \alpha = \dot{\alpha}, \quad \dot{\alpha}_0 = 0$$

The coefficients in the above equation are given in terms of aerodynamic mass and gravitational quantities. Applying to them the same trim conditions and approximations as were applied to the equations, one obtains ( $i_t = 0 =$  thrust line angle).

$$a) D_V = \frac{\bar{q} S}{m V_0} \left( 2 C_{D_0} + V_0 \frac{\partial C_D}{\partial V} \right) - \frac{1}{m} \frac{\partial T}{\partial V}$$

No data were supplied for  $\frac{\partial C_D}{\partial V}$  and, hence, this term was assumed zero for the simulation, giving

$$D_V = \frac{1 \rho V_0 S}{m} \cdot C_{D_0} - \frac{1}{m} \frac{\partial T}{\partial V} = \frac{1}{m} \left[ \rho V_0 S C_{D_0} - \frac{\partial T}{\partial V} \right] = 0.051/\text{sec}$$

$$\begin{aligned} b) D_\alpha &= -g (\sin \alpha_0 \sin \theta_0 + \cos \alpha_0 \cos \theta_0) + \frac{\bar{q} S}{m} C_{D_\alpha} + \frac{T}{m} \sin \alpha_0 \\ &= -g \cos (\theta_0 - \alpha_0) + \bar{q} S/m C_{D_\alpha} + T/m \sin \alpha_0 \\ &= -g \cos \gamma_0 + \bar{q} S/m C_{D_\alpha} + T \alpha_0/m \end{aligned}$$

where  $\gamma_0$  is the flight path angle at trim specified as approximately  $-3^\circ$  glide slope in the simulation problem. Hence,  $\cos \gamma_0 \approx 1$

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$$\therefore D_{\alpha} = 1/m \left[ \bar{q} S C_{D\alpha} + T\alpha_0 - W \right] = -16.5 \text{ fps}^2/\text{rad}$$

$$\begin{aligned} \text{c) } D_{\theta} &= g (\cos \alpha_0 \cos \theta_0 + \sin \alpha_0 \sin \theta_0) \\ &= g \cos (\theta_0 - \alpha_0) = g \cos \delta_0 \approx g = 32.2 \text{ fps}^2/\text{rad} \end{aligned}$$

$$\text{d) } D_{\delta e} = -\frac{\bar{q} S}{m} C_{D\delta e} \approx 0 \quad (\text{assumed negligible in the simulation})$$

$$\text{e) } D_{\delta_T} = \frac{\cos \alpha_0}{m} \frac{\partial T}{\partial \delta_T} \approx \frac{1}{m} \frac{\partial T}{\partial \delta_T} = 740 \text{ fps}^2/\text{in throttle cable travel}$$

## Note

In this simulation, the acceleration due to thrust of the B-26 was computed and applied directly as the equivalent thrust acceleration of the C-5A. It was decided that this was the simplest way of correctly interpreting pilot application of throttle on the B-26 in terms of the corresponding effect on the C-5A drag equation.

$$\text{Hence } \frac{\Delta T_{B-26}}{m_{B-26}} = \frac{\Delta T_{C-5A}}{m_{C-5A}} = \dot{V}_T \text{ (acceleration due to thrust)}$$

where  $\Delta T$ 's are incremental thrust from engage setting

$$\text{and } \Delta T_{B-26} = \left( \frac{\partial T}{\partial \delta_T} \right)_{B-26} \Delta \delta_T$$

$\Delta \delta_T$  in inches of throttle cable movement

$$\therefore \dot{V}_T = \frac{1}{m_{B-26}} \left( \frac{\partial T}{\partial \delta_T} \right)_{B-26} \Delta \delta_T$$

$$\begin{aligned} \text{f) } \gamma_V &= -\frac{\rho S}{2m} \left[ 2 \sin \alpha_0 C_{D0} + V_0 \sin \alpha_0 \frac{\partial C_D}{\partial V} + 2 \cos \alpha_0 C_{L0} \right. \\ &\quad \left. + V_0 \cos \alpha_0 \frac{\partial C_L}{\partial V} \right] \text{ for } \beta_0 = 0 = C_{\bar{V}_0} = \frac{\partial C_{\bar{V}}}{\partial V} \text{ and } i_{\bar{c}} = 0 \end{aligned}$$

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Also, the simulation assumes  $\frac{\partial C_D}{\partial V} = \frac{\partial C_L}{\partial V} \approx 0$  and  $\cos \alpha_0 = 1$  while  $\sin \alpha_0 = \alpha_0$  (rad); Hence

$$\dot{z}_V = -\frac{\rho S}{2m} \left[ 2\alpha_0 C_{D_0} + 2C_{L_0} \right] = -\frac{\rho S}{m} \left[ C_{L_0} + \alpha_0 C_{D_0} \right] = -.00156/\text{ft}$$

$$g) \dot{z}_\alpha = -\frac{\bar{q} S}{mV_0} \left[ \sin \alpha_0 C_{D_\alpha} + \cos \alpha_0 C_{D_0} + \cos \alpha_0 C_{L_\alpha} - \sin \alpha_0 C_{L_0} \right]$$

which, with previous assumptions, reduces further to

$$\dot{z}_\alpha = -\frac{\bar{q} S}{mV_0} \left[ \alpha_0 C_{D_\alpha} + C_{D_0} + C_{L_\alpha} - \alpha_0 C_{L_0} \right]$$

For unaccelerated flight, the thrust force balances the gravity and aerodynamic forces. Hence, one may write

$$T_0 = -L_0 \sin \alpha_0 + D_0 \cos \alpha_0 + W \sin \theta_0$$

$$\therefore T_0 - W \sin \theta_0 = D_0 \cos \alpha_0 - L_0 \sin \alpha_0$$

Applying the trigonometric approximations and putting  $\bar{q} S C_{D_0} = D_0$  and  $\bar{q} S C_{L_0} = L_0$ , one obtains

$$T_0 - W \theta_0 = \bar{q} S (C_{D_0} - C_{L_0} \alpha_0)$$

Substituting this into the expression for  $\dot{z}_\alpha$ , the result becomes,

$$\dot{z}_\alpha = -\frac{1}{mV_0} \left[ (\alpha_0 C_{D_\alpha} + C_{L_\alpha}) \bar{q} S + T_0 - W \theta_0 \right] = -0.388/\text{sec-rad}$$

$$h) \dot{z}_\theta = -\frac{g}{V_0} \sin \theta_0 \approx -\frac{g \theta_0}{V_0} = -.0218 \text{ rad/sec}$$

$$i) \dot{z}_{\delta e} = -\frac{\bar{q} S}{mV_0} (C_{D_{\delta e}} \sin \alpha_0 + C_{L_{\delta e}} \cos \alpha_0)$$

# Contrails

But  $C_{D\delta_e} \approx 0$ ,  $\cos \alpha_0 \approx 1$

$$\therefore \dot{\delta_e} = -\frac{\bar{q} S}{m V_0} C_{L\delta_e} = -.0230/\text{sec-rad}$$

k)  $m_{\dot{\alpha}} = \bar{q} \frac{S \bar{c}}{I_Y} \frac{\bar{c}}{2 V_0} C_{m\dot{\alpha}}$

l)  $m_{\alpha} = \bar{q} \frac{S \bar{c}}{I_Y} C_{m\alpha}$

m)  $m_{\dot{\phi}} = \bar{q} \frac{S \bar{c}}{I_Y} \frac{\bar{c}}{2 V_0} C_{m\dot{\phi}} = -0.284/\text{sec}$

n)  $m_{\delta_e} = \bar{q} \frac{S \bar{c}}{I_Y} C_{m\delta_e}$

The coefficients for which no numerical values have been specified thus far are those listed in the schedule on page 18 which was derived to obtain the required configuration for the experiment. The only mode parameter variable for the different configurations is the frequency of the short-period mode. The other parameters are kept constant as specified earlier in the report. The lateral equations used for analysis during the investigation are:

$$\begin{vmatrix} S - Y_{\beta} & 1 + \alpha\theta + Y_p\theta - Y_r & -g/V - S(\alpha + Y_p) \\ -L_{\beta} & -S\theta + L_p\theta - L_r & S^2 - S L_p \\ -N_{\beta} & S + N_p\theta - N_r & -S N_p \end{vmatrix} \begin{vmatrix} \beta \\ r \\ \phi \end{vmatrix} = \begin{vmatrix} Y_{\delta_r} \delta_r \\ L_{\delta_a} \delta_a + L_{\delta_r} \delta_r \\ N_{\delta_a} \delta_a + N_{\delta_r} \delta_r \end{vmatrix}$$

$Y_{\beta}$	=	-0.0913	$L_{\delta_a}$	=	-0.444	$I_x$	=	$19 \times 10^6$
$Y_p$	=	0.0264	$L_{\delta_r}$	=	0.1123	$I_z$	=	$44 \times 10^6$
$Y_r$	=	0.0267	$N_{\beta}$	=	0.248	$I_{xz}$	=	$1.37 \times 10^6$
$Y_{\delta_r}$	=	0.0219	$N_p$	=	-0.176	$b$	=	219 ft
$L_{\beta}$	=	-0.847	$N_r$	=	-0.175	$S$	=	5900 sq ft
$L_p$	=	-0.865	$N_{\delta_a}$	=	-0.027	$\bar{c}$	=	30.14 ft
$L_r$	=	0.883	$N_{\delta_r}$	=	-0.164	$m$	=	18160 slugs

## APPENDIX II

### CONSIDERATIONS PERTAINING TO RATING SYSTEM

The range of pilot rating is the maximum numerical rating minus the minimum numerical rating.

The standard deviation is

$$S_R = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}} = \sqrt{\frac{n}{n-1} \left[ \frac{\sum x_i^2}{n} - \left( \frac{\sum x_i}{n} \right)^2 \right]}$$

where  $x_i$  is the  $i^{\text{th}}$  rating,  $\bar{x}$  is the mean rating, and  $n$  is the total number of ratings for a particular configuration. The variance is  $S_R^2$ .

An explanation of the meaning of the average ratings is in order because of the effect of the tendency to balloon on flare and the pilot's attempts to allow for this effect in their ratings. It is believed that the ballooning tendency, which is a result of the B-26 value of  $L_{\alpha}$  in the angle-of-attack response, is not representative of the C-5A flare. This belief was pointed out to the pilots, and it was suggested that they rate the overall airplane for the ILS portion of the landing approach separately from rating it for the inclusion of the flare. Complete success in this division of ratings was not attained because, in their comments, the pilots do not always explicitly state what their ratings are for. That is, there are ratings defined for the ILS portion only, for the whole task including the flare, and some that are unidentified. The unidentified ratings are assumed to pertain to the ILS portion only for all flights of pilots D and E and for all flights after the first one for each of pilots B and C. This assumption is based on the fact that the decision to split the ratings was made after the first flights of pilots B and C were made. After the decision was made to split the ratings, the safety pilot generally disengaged the variable-stability system and took control of the airplane early in the flare maneuver. This act kept the pilots from seeing and rating the flare. It is suspected that the majority of pilot A's ratings include the flare. The average ratings that are presented in Table IX exclude those ratings that are known to include the flare. However,

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some of the ratings included in the averages may have been for the flare, and this may contribute to the variance of the ratings for some of the longitudinal configurations.

The pilot's comments concerning the characteristics of each configuration are tabulated in summarized form in Tables IV through X.

PILOT COMMENTS FOR LONGITUDINAL EVALUATION

LONGITUDINAL

PILOT	CONFIG	LONGITUDINAL							LATERAL							RATING				
		EASE OF MAKING SMALL $\phi$ CORRECTIONS	$\phi$ FOR FLARE AND OTHER MANEUVERING	TRIM SENSITIVITY	THROTTLE RESPONSE	THRUST TO HOLD Y & A IN A TURN WITH $\phi = 30^\circ$	$F_{ES}$	$\delta_{ES}$	LATERAL	INITIATING TURN	STOPPING TURN OR HEADING	ROLL POWER	HELP WITH COME UP WITH HEADING	CHANGE OF HEADING	$\delta_a$ LAG	GENERAL	TURBULENCE	ILS NORMAL FLYING	FLARE	LATERAL
A	D	SLOW, THEN SPEEDS UP; PIO					REASONABLE			DIFFICULT		INADEQUATE		CAN'T CONTROL BECAUSE OF ROLL CONTROL		SPIRAL IS UNSTABLE		5	6	8
B		VERY GOOD FOR LARGE AIRPLANE	SATISFACTORY SLIGHT OVERSHOOT OF $\phi$	SATISFACTORY	SATISFACTORY	CONSIDERABLE	REASONABLE	VERY GOOD FAIRLY SMALL	COMPLETELY UNSATISFACTORY	NOT EASY SMOOTH START	OVERSHOOT; NOT EASY SMOOTH START		VERY DEFICIENT	YES, HARD TO	REASONABLE ONLY IN SMOOTH AIR	VERY EXCESSIVE		3	4	8
		LIKED IT					ONE HAND, LIGHT, PLEASANT						CONSIDERABLY MORE					3		
C		OSCILLATE DIFFICULT	SLIGHT TENDENCY TO PIO	FAIRLY WELL DEFINED		NEED POWER TO GET BACK ON RATE OF DESCENT	NOT MUCH FORCE	LITTLE GREAT	OSCILLATE IN HEADING				NOT ENOUGH SLOW	DIFFICULT TO HOLD HEADING	LAGS QUITE SLOW	LT.		5 (BASED ON LATERAL DIRECTIONAL)		
		QUITE FAST, MAY BE TOO FAST RESPONSE	PIO ON FLARE				LIGHT	RELATIVELY SMALL								SMALL ANDRY		4-1/2		
D		LOW RESPONSE NOT FAIRLY EASY		SLOPPY IN TRIM, SENSITIVITY IS QUITE EFFECTIVE			RATHER LIGHT, EFFECT IS RATHER LOW	HIGH COMPARED TO YES	USE TWICE AS MUCH RUDDER AS NECESSARY PRIMARY PROBLEM	VERY HIGH DELAY, THEN BIG TURN HANGI TUBES, DIFFICULT		VERY SLOW TO STOP TURN RATE	LITTLE INADEQUATE NOT ACCEPTABLE	EXCESSIVE ADVERSE YAW		LET G.S. GET OFF JUST DOING LATERAL	SOME, BUT DON'T SAY HOW MUCH		4-1/2	6-1/2
		LAG DELAY: RELATIVELY EASY, PORPOISE		PRETTY GOOD, FAIRLY EFFECTIVE			OK - LOW TOO LOW	LARGE EXCESSIVE												
E		EASY			NO PROBLEM		RATHER LIGHT REASONABLE										QUITE LIGHT	5		8
				NOT TOO DIFFICULT	REALISTIC		VERY LIGHT: TOO LIGHT	QUITE A BIT TOO MUCH									MOD	4		
A	F	MORE PRECISE AIRPLANE EASIER		REASONABLY WELL DEFINED, SENSITIVITY IS OK			GOOD	GOOD							LONG, NOT ACCEPTABLE	REASONABLY ROUGH		3-1/2		9
B								PERHAPS SMALLER THAN ON D										3	4 PORPOISE	
		REASONABLE, EASY						$F_{ES}/S$ IS REASONABLE, ONE HAND										3		
C		FAIRLY RESPONSIVE					WASN'T BOTHERSOME	PRETTY GOOD											3-1/2	7
		FAIRLY GOOD					MODERATE	SMALL											3-1/2	
D		PORPOISE																	5	4-1/2
		BEST OF ALL TESTED, SOME DELAY		MORE POSITIVE			GOOD	BEST											3-1/2	5
E				EASY RECOGNIZABLE	NOMINAL		LIGHT, GOOD	SMALL	$\phi$ IS BIGGEST PROBLEM					OSCILLATE ABOUT HEADING		RUDDER FORCES ARE HIGH			5	
		EASY	SMALL PIO				GOOD	SUITABLE									LT-MOD	3		
A	H	SLOWER RESPONSE FAIR EASE	PULLED UP TOO MUCH ON FLARE		GOES AS EXPECTED		LIGHT	LARGER THAN I LIKE	JUST TERRIBLE										6	9
B			ONCE STARTED KEEPS COMING																3	5, 8 REARS UP MORE
		REASONABLE					RELATIVELY LOW	MORE TRAVEL TOO MUCH PIO											4	
C		HAVE TO WORK AT IT, FAIRLY DIFFICULT, SLOW PIO	COULD PIO EASILY	EFFECTIVE BUT DON'T USE IT BECAUSE LIGHT FORCE			FAIRLY LIGHT, QUITE LIGHT	LITTLE SLOPPY											9	
D		SLUGGISH, OVERDRIVE IT SPONGY	OVERCONTROL, TOO SLOW COMING UP	NOT SOLID POINT, NOT SENSITIVE ENOUGH			LITTLE LIGHT	PRETTY LARGE		TOO MUCH ADVERSE YAW	TURBULENCE, OVERSHOOT		MORE THAN YOU NEED	LOT OF DIFFICULTY HOLDING		APPEARS REDUCED WITH THIS HIGH ROLL RATE			5	6
E		RATHER HARD TO MAKE		MORE DIFFICULT BECAUSE OF SLOP IN CONTROLS			VERY LIGHT	LARGE												
		VERY DIFFICULT MUST ANTICIPATE	ANTICIPATE TO CHECK NOTION PIO	DOES NOT RETURN RAPIDLY TO TRIM			QUITE LIGHT TOO LIGHT	HIGH						HOLD HEADING IS MOST DIFFICULT					7	9 (HARD TO PICK UP WING)



**PILOT COMMENTS FOR LONGITUDINAL EVALUATION**

LONGITUDINAL

PILOT	CONFIG	LONGITUDINAL							LATERAL							RATING				
		EASE OF MAKING SMALL $\phi$ CORRECTIONS	$\phi$ FOR FLARE AND OTHER MANEUVERING	TRIM SENSITIVITY	THROTTLE RESPONSE	THRUST TO HOLD V & H IN A TURN WITH $\phi = 30^\circ$	$F_{ES}$	$\delta_{ES}$	LATERAL	INITIATION TURN	STOPPING TURN OR HEADING	ROLL POWER	HELP WING COME UP WITH RUDDER	CHANGE OF HEADING	$\delta_{LAG}$	GENERAL	TURBULENCE	ILS NORMAL FLYING	FLARE	LATERAL
A	I	SLOW RESPONSE P10 OVERSHOOT		TRIM PT. NOT WELL DEFINED. SENSITIVITY IS O.K.	QUITE REASONABLE			NOT EXCESSIVE SORT OF REASONABLE	SLOW RESPONSE	NOT EASY LAG	HARD	CAN'T PICK UP A WING IN TIME		WALLOWS AROUND	BOTHER	SPIRALLY UNSTABLE	LITTLE BIT ROUGH			
B		ZERO PITCH BUMPING OR ZERO ST. STABILITY. DIVERGENT IN $\phi$						HIGH TO START $\phi$ - TURNS OUT TO BE ZERO, HEAVY										8	9	
C		DIFFICULT. OVER-CORRECT. SLOW	OSCILLATE ON WIDE SLOPE P10					VERY HEAVY		DIFFICULT	DIFFICULT						MOD.			LATERAL
D		OVERSHOOT. ALMOST IMPOSSIBLE. OVERDRIVE IT	SMOOTH IF CAREFUL OTHERWISE PORPOISE	RATHER SLOPPY NOT WELL DEFINED				TOO HEAVY TOO HIGH								SLOPPY LONGITUDINALLY		7	9	
E			P10	DIFFICULT INSENSITIVE				VERY HIGH									MODERATE		8	P10
A	J	SLOW RESPONSE. LAG IN STARTING OVERSHOOT	MUST USE GREAT CARE TO AVOID P10	MODERATELY WELL DEFINED POINT	NORMAL			HEAVY AND SPONGY	MARGINAL	HARD	HARD	CAN'T GET WING UP SOON ENOUGH					SMOOTH		7	8
B		BE VERY TENDER TO PREVENT P10	OK SMOOTH AIR	WELL DEFINED	SATISFACTORY			LIGHT $F_{ES}/\delta_{ES}$ P10	FAIRLY DECENT FOR SMALL SLOW INPUTS. SMOOTH AIR. UNDESIRABLE FOR SMALL INPUTS			OK IN SMOOTH AIR FROM SMALL $\phi$	ADEQUATE FOR SMOOTH AIR							6 ON 1ST PASS 5 ON 2ND PASS
C		PITCH IS TOO RAPID, HARD P10	P10					FAIRLY HIGH										5	8	
D		MORE RESPONSIVE BUT STILL A LAG OSCILLATE		OSCILLATE ABOUT TRIM POINT. TRIM SENSITIVITY O.K.	NO GREAT EFFECT ON AIRPLANE			NOT EXCESSIVE. NOT TOO BAD								DEEP LONG. PRETTY WELL			5	5-1/2
E		VERY DIFFICULT P10		DIFFICULT TO DEFINE POINT	REALISTIC			HIGH									LIGHT GUSTS		5	
A	K	SLOW RESPONSES. FAIRLY EASY & DON'T P10 MUCH		SO SLOW RESPONDING YOU MUST FLY AIRPLANE BACK				RATHER HIGH NOT EXCESSIVE	POOR			CAN'T PICK UP WING CLOSE TO THE GROUND							4	7
B		VERY SLOBBISH	PORPOISE DUE TO SLOBBISH RESPONSE	WELL DEFINED															6	9
C		SLOW RESPONSE P10						NOT TOO HIGH									MOD.	5-1/2	9	LATERAL
D		EXCESSIVE LAG. OVER-CONTROL NOT GOOD	OVERCONTROL PORPOISE	NO STRONG RETURN				LITTLE BIT HIGH				HIGH		SPIRAL INSTABILITY MAKE IT HARD		LONG. LOW UNDAMPED FREQUENCY			5	9
E		NOT VERY EASY LAG	P10	NOT TOO WELL DEFINED	TYPICAL			TOO LIGHT FOR $\delta_{ES}$ YOU GET											8	

**PILOT COMMENTS FOR LONGITUDINAL EVALUATION**

LONGITUDINAL

PILOT	CONFIG	LONGITUDINAL							LATERAL										RATING		
		EASE OF MAKING SMALL @ CORRECTIONS	δ FOR FLARE AND OTHER REMEMBERING	TRIM SENSITIVITY	THROTTLE RESPONSE	THROTTLE TO HOLD V & δ IN A TURN WITH δ = 30°	F <sub>rs</sub>	δ <sub>rs</sub>	LATERAL	INITIATING TURN	STOPPING TURN OR HEAD ON	ROLL POWER	HELP WIND COME UP WITH SUGGER	CHANGE OF HEADING	S <sub>o</sub> LAG	GENERAL	TURBULENCE	ILS NORMAL FLYING	FLARE	LATERAL	
A	L	SLOW RESPONSE BUT NOT TOO BAD	EASY TO ESTABLISH BALANCE	REASONABLY WELL DEFINED POINT	SATISFACTORY		LITTLE LIGHT	EXTREME AMPHIB											6	8	
B	L	DIFFICULT TO START TO STOP IT, VERY SLOWISH	PIO					GREATER											6	8	
C	L	SLOWISH PIO	SLOW TO START, PIO	NOT EASILY DEFINED			FAIRLY LIGHT										CALM	6	7	8 OR 7 IN CALM AIR	
D	L	EARLY BUT STILL DIFFICULT		RATHER INEFFECTIVE			LIGHTER, MORE LIKE	EXCESSIVE									LT. TO OCCASIONAL MOD.	5 1/2			
E	L	FAIRLY EASY	PIO	NOT MUCH DIFFICULTY, VERY DIFFICULT	VERY EASY TO SET UP RATE OF DESCENT		VERY LIGHT	EXCESSIVE										7	6		
A	0	SLOW, HARD TO DO ANYTHING (F <sub>rs</sub> )	SLOW OSCILLATION ON THE APPROACH	MODERATELY WELL DEFINED PT.	REQUIRES TRIM TAB		EXTREMELY HEAVY	NOT VERY GREAT											6	8	
B	0	QUITE SLOW INITIALLY THEN OVERSHOTS					HEAVY PRESSURE VERY HEAVY	VERY SMALL INORDINATE												8	
C	0	PIO SLOW RESPONSE	LATE RESPONSE PIO	HARD TO DEFINE FOR HEAVY FORCES			MAY TOO MUCH	QUITE RESTRICTED									LIGHT	5	6 1/2		
D	0	LARGE TIME DELAY & SLOW REACTION, BUT EASY	POORISE, BUT LESS TENDENCY BECAUSE OF HIGH F <sub>rs</sub>	NOT REAL POSITIVE POINT	NO RESPONSE		MAY TOO HIGH	EXCESSIVE FOR RESPONSE									RELATIVELY LIGHT	4 1/2 5 1/2	6 1/2 6		
E	0	VERY DIFFICULT PIO	DIFFICULT TO STOP MOTION WHERE YOU WANT IT	SENSITIVE	REALISTIC		VERY HIGH	FAIRLY GOOD									LITTLE BUMPY		8		
A	S	LITTLE PROMPTER RESPONSE, CAN OVERSHOOT IN PITCH	BETTER TO NO LITTLE CONTROLLING	BETTER DEFINED TRIM POINT			HIGH	NOT MUCH, SMALL											7		
B	S	RESPONSE IS QUICKER	PIO				HEAVY TO INITIATE RESPONSE	WOULD LIKE F <sub>rs</sub> & δ <sub>rs</sub> REDUCED											7		
C	S	OSCILLATE BUT CAN DO IT		LITTLE DIFFICULT TO DEFINE	STARTS A PITCH OSCILLATION		FAIRLY HIGH	NOT VERY GREAT									LIGHT	5	6		
D	S	LAG, SMOOTH AT 0.1, TURN OVERCONTROL	OVERCONTROL	OVERCONTROL, OSCILLATE, NOT REAL POSITIVE POINT			EXCESSIVE										LIGHT TO MOD.	4 1/2	7 1/2		
E	S																LT. TO MOD.		6	6	

Table VII  
PILOT COMMENTS FOR LONGITUDINAL EVALUATION

		LONGITUDINAL										LATERAL					RATING			
PILOT	CONFIG	EASE OF MAKING SMALL $\theta$ CORRECTIONS	$\theta$ FOR FLARE AND OTHER MANEUVERING	TRIM SENSITIVITY	THROTTLE RESPONSE	THRUST TO HOLD Y & H IN A TURN WITH $\phi = 30^\circ$	$F_{ES}$	$\delta_{ES}$	LATERAL	INITIATING TURN	STOPPING TURN ON HEADING	ROLL POWER	HELP WING COME UP WITH RUDDER	CHANGE OF HEADING	$\delta_a$ LAG	GENERAL	TURBULENCE	ILS NORMAL FLYING	FLARE	LATERAL
A	BASE																			
B																				
C		FAIRLY EASY, VERY SLIGHT DELAY		BIT HARD TO CENTER, SENSITIVE			MODERATE	MODERATE												
D		FAIRLY EASY, NO PURPOSE		EFFECTIVE, DEFINITE			GOOD	GOOD												
E																				
A																				
B																				
C																				
D																				
E																				
A																				
B																				
C																				
D																				
E																				

**PILOT COMMENTS FOR LATERAL EVALUATION**

LATERAL

PILOT	CONFIG	LONGITUDINAL							LATERAL									RATING		
		EASE OF MAKING SMALL $\phi$ CORRECTIONS	$\phi$ FOR FLARE AND OTHER MANEUVERING	TRIM SENSITIVITY	THROTTLE RESPONSE	THRUST TO HOLD V & H IN A TURN WITH $\phi = 30^\circ$	FES	DES	LATERAL	INITIATING TURN	STOPPING TURN OR HEADING	ROLL POWER	HELP WING COME UP WITH RUDDER	CHANGE OF HEADING	$\delta_r$ LAG	GENERAL	TURBULENCE	ILS NORMAL FLYING	FLARE	LATERAL
A	H	OVERSHOOT					RATHER LIGHT	LARGE	USE RUDDER TO FORCE TURN RATE	LAG, THEN STARTS	FAIRLY EASY	CAN PICK UP A WING QUITE WELL							5	
B										O.K. WITH SMALL INPUTS	O.K. FOR SMALL TURNS	EXCELLENT						5	5	
C										DIFFICULT TO COORDINATE, BE DELIBERATE	O.K. IF YOU'RE SLOW AND DELIBERATE	MODERATE			DIFFICULT TO MAKE SMALL ONES	NOT PRONOUNCED			4	
D										VERY HARD TO COORDINATE, RATE, LOT OF RUDDER	VERY HARD TO COORDINATE, RATE HIGH $\delta_r$	LITTLE LAG THEN QUITE HIGH $\delta_r$ FLERTY			SKID IT, TO HOLD IS FAIR	PRETTY GOOD		LONG 3	1.5 TIME TO TURN	
E		EASY		EASY	NORMAL		PRETTY FAIR	REASONABLE				QUITE GOOD						5	5	
A	O								HARD TO MAKE SMALL CORRECTIONS			SLOW OVER-SHOOT IN ROLL RATE, TEND TO PICK UP WING			NOT VERY ACCURATELY	PRONOUNCED LAG			LITTLE BIT	6
B												UNACCEPTABLY SMALL	EXTENSIVE, VIGOROUS		DIFFICULT	UNACCEPTABLY LARGE				9
C									EXTREMELY SLOW, SLUGGISH			VERY LOW	USE FULL $\delta_r$				UNFLYABLE FOR PRECISION INSTRUMENTS			10
D									HORRIBLE, DUTCH ROLL UNCONTROLLING	HARD TO START, SKID IT	HARD TO STOP	MAY LOW	RATHER INEFFECTIVE		2 - 2 1/2 SEC. BEFORE RESPONSE			MOD.		8-1/2
E												VERY POOR	COMB ON IT			QUITE SLOW				8
A	P																			
B										SLUGGISH										7
C									LITTLE SLOW	O.K.					O.K. IF CAREFUL	SLIGHT	$\delta_r$ FORCES ARE FAIRLY HEAVY	LT. TO MOD.		8 1/2 (OR 9 IN THE FLARE BECAUSE IF A WING GOES DOWN, YOU CAN'T GET IT UP FAST ENOUGH)
D									EASE IT INTO TURN, USE LOTS OF RUDDER	FAIR TO GOOD	INADEQUATE			SKID IT	EXCESSIVE			SMOOTH HIGH MOD. LOW		6 (2/3 TIME FOR LATERAL)
E									EASY IF YOU CAN DO IT SLOWLY			VERY LOW	REQUIRED		90% OF TIME MAINTAINING HEADING	ABOUT 1 SEC		PIO BANK ANGLE		8

Table IX  
PILOT COMMENTS FOR LATERAL EVALUATION

PILOT	CONFIG	LONGITUDINAL							LATERAL								TURBULENCE	RATING		
		EASE OF MAKING SMALL CORRECTIONS	G FOR FLARE AND OTHER MANEUVERING	TRIM SENSITIVITY	THROTTLE RESPONSE	THRUST TO HOLD V & H IN A TURN WITH $\phi = 30^\circ$	FES	SES	LATERAL	INITIATING TURN	STOPPING TURN OR HEADING	ROLL POWER	HELP W/ IRE COME UP WITH RUDDER	CHANGE OF HEADING	$\delta$ LAG	GENERAL		ILS NORMAL FLYING	FLARE	LATERAL
A	R																			
B											MODERATE, BUT ACCEPTABLE. REASONABLE.	EXCESSIVE HELP REQUIRED	OK IF WILLING TO WAIT LONG TIME	VERY EXCESSIVE					8	
C											LOW		WAIT 2 SEC FOR SOMETHING TO HAPPEN	$\delta$ FORCES ARE QUITE HIGH				8		
D									SHOWS AIR FLYABLE, BUT TURBULENCE EXTREMELY DIFFICULT	EASY TO STOP IN AIR	OK IN SMOOTH AIR, BUT CHANGING IN TURBULENCE					MOD. DOWN LOW		6 1/2		
E											STARTS SLOWLY & THEN PICKS UP RAPIDLY. VERY POOR.								7	
A	T																			
B										GOOD FOR SMOOTH, LOW RATE	GOOD	ADEQUATE			VERY SHORT				4	
C											FAIRLY RAPID, PLIGHT OF POWER		POSSIBLE IF CAREFUL & DELIBERATE	SLIGHT	$\delta$ FORCES ARE MEDIUM				4	
D									CAN'T BE PRECISE ON LOCALIZER	REQUIRE LOTS OF COORDINATING RUDDER	LOTS OF RUDDER	HIGH	GOOD $L_p$	DIFFICULT TO DO QUICKLY & PRECISELY	LEADS TO OVERCONTROL PID				6	
E									$\delta$ FORCES ARE QUITE LIGHT			GOOD PID				MODERATE			6	
A	U								SOMewhat "BOLLEY" (LAW)	USE RUDDER TO HELP GET TURN RATE		RATHER ADEQUATE		LACK OF PRECISION, OSCILLATE	NOT GREAT NOTICEABLE	PICK UP WING RATHER EASILY			4	
B										EASY	SMOOTH LAG, FREE	ADEQUATE			LOW				4	
C									$\rho$ PRODUCES $\beta$	USE LOT OF RUDDER	OVERSHOOT A LITTLE BIT		$\rho$ IS SLOW TO START	NOT BIG	CONTROL FORCES FEEL FAIRLY GOOD	ALMOST CALM	5 1/2	3		
D									LOWER PERIOD DUTCH ROLL	EASIER, BUT NEED LOTS OF RUDDER	NEED LOTS OF RUDDER	ADEQUATE	HOLD HEADING PRETTY GOOD	DISCONCERTING OSCILLATE		VERY LT.		4 1/2		
E									$\beta$ WITH $\rho$	EASY		VERY GOOD			VERY LITTLE	OCCASIONAL LT. TO MOD			5	

PILOT COMMENTS FOR LATERAL EVALUATION

LATERAL

PILOT	CONFIG	LONGITUDINAL							LATERAL								RATING			
		EASE OF MAKING SMALL $\theta$ CORRECTIONS	$\theta$ FOR FLARE AND OTHER MANEUVERING	TRIM SENSITIVITY	THROTTLE RESPONSE	THRUST TO HOLD $\gamma$ & $\alpha$ IN A TURN WITH $\phi = 30^\circ$	$F_{ES}$	$\delta_{ES}$	LATERAL	INITIATING TURN	STOPPING TURN ON HEADING	ROLL POWER	HELP WING COME UP WITH RUDDER	CHANGE OF HEADING	$\delta_n$ LAG	GENERAL	TURBULENCE	ILS NORMAL FLYING	FLARE	LATERAL
A	V							SOMEWHAT "ROLLEY"	TEND TO OVERSHOOT LEADS TO "ROLLEY"		RATHER LIMITED		HARD BECAUSE OF OSCILLATION IN YAW	INDUCES ROLLINESS		LIGHT			7	
B									SLUGGISH	SLUGGISH, NOT ANTICIPATE	MEDIUM	MUST USE SEVERAL CASES		LARGE INADEQUATE					6	
C									LITTLE DIFFICULT TO INITIATE	LITTLE DIFFICULT	SOMEWHAT		LITTLE BIT SLOW		8 IS LITTLE BIT HEAVY	CALM			5	
D								APPREHENSIVE BECAUSE OF LOW ROLL POWER	AGAINST STOP OF WHEEL IF LARGE TURN RATE WANTED	INADEQUATE ROLL POWER TO STOP IT WHERE WANT	INADEQUATE			WANTS LESS LAG	WOULD BE IMPOSSIBLE IN HEAVY TURBULENCE	LT.			7-1/2	
E										EASY TO OVERSHOOT	NOT ENOUGH PIO			BIGGEST PROBLEM					6	
A	W							HARD STOPPING ROLL TEND TO OSCILLATE	WAIT TO GET IT STARTED	WAIT TO GET IT STOPPED	VERY LIMITED TAKES LONG TIME TO PICK UP WING								6	
B									NEED TO HELP WITH RUDDER	APT TO OVERSHOOT	LOW DEFICIENT	IS REQUIRED		LOW					6	
C									DIFFICULT TO START	MOST DIFFICULT	VERY LOW	USE A GREAT DEAL		$\delta_n$ HEAVY	OCCASIONAL LT.			6 (TOO SLOW TO CORRECT ON OFFSET)		
D									AMOUNT OF $\theta$ IS CRITICAL		EVER LESS ROLL POWER THAN $\gamma$	RUDDER PRODUCE EXCESSIVE $\beta$	DIFFICULT BECAUSE OF LAG		NO MORE THAN $\theta = 20^\circ$ OR LOSE CONTROL IN TURBULENCE			6-1/2		
E									DIFFICULT LAG		INSUFFICIENT	YES		EXCESSIVE		LT.			6	
A	Z										LIMITER: CAN STOP $\theta$ WHERE YOU WANT IT		CHANGE OF HEADING IS POSSIBLE	BETTER IDEA OF WHAT IS GOING ON					6 (PRIMARILY BECAUSE OF LOW ROLL AUTHORITY)	
B									LITTLE LAG	LITTLE LAG			JUST ACCEPTABLE	A LITTLE					7	
C									EASY TO INITIATE	STOP ON HEADING BY USING QUITE BIT OF RUDDER	BIT LOW		FAIRLY ACCURATE	SLIGHT; HURDED DELAY FOR BIG INPUT	$\delta_n$ FORCE IS LIGHT TO MEDIUM	OCCASIONAL LT.			6-1/2	
D									QUITE A BIT OF RUDDER	NOT PRECISE SO END UP CORRECTING WITH RUDDER	LOW INADEQUATE					LT. TO MOD.	3-1/2		5-1/2	
E											NEED FULL WHEEL, NOT TOO SAG			NOT TOO BIG		VERY LIGHT			6	

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# *Contrails*



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<b>13. ABSTRACT</b>  Expected ranges of unaugmented longitudinal and lateral-directional handling qualities of the C-5A class airplane were simulated and evaluated in a variable-stability B-26 for the instrument-landing. The longitudinal short period undamped frequency was given three values, 0.64, 0.10, and 0.16 cps, and a short period damping ratio of 0.7 was maintained. The elevator stick force and stick motion gradients were given two values each--60 lb/g and 100 lb/g, and 8 in/g and 2/in/g, respectively. The lateral directional parameters $\frac{pb}{2u}$ and $\tau_R$ were each given values of 0.08, 0.14, and 0.22 for $\frac{pb}{2u}$ and $\tau_R$ were each given 0.6, 1.0 and 1.4 for $\tau_R$ . Although $\tau_{u,max}$ many of the configurations were judged to be acceptable, none were satisfactory, thus implying that stability augmentation is probably required.		

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