Theory and Flight Verification of the TIFS Model-Following System

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The content of this paper describes the theoretical development and flight-test results of the model-following control system of the Air Force Total In-Flight Simulator (TIFS). A discussion of the conceptual design and detailed development of the system configuration is given. The manner in which the feedforward, gust compensator and lateral-directional feedback gains are obtained is developed. The feedforward and gust compensator gains are obtained by simple matrix algebra calculations. A sensitivity minimization approach using modern control theory is used to obtain the lateral-directional feedback gains. Digital simulation results are included to show the improvement in model-following achieved with the feedback gains determined by this approach. Time histories of the model and TIFS responses from flight test are also included to show the quality of model-following obtained with the system for both the lateral-directional and longitudinal modes of operation. These results verify the theory and design procedure used to obtain the TIFS model-following control system.

Nomenclature

e_{xi} = error signal = $x_{i_m} - x_i$
F = a square matrix of the dimensional stability derivatives of the simulator
G = matrix of dimensional control derivatives of the simulator
J = the turbulence effectiveness matrix whose elements define the forces and moments produced on the simulator by gusts
ΔK = perturbation to initial value of feedback matrix
K_g = gust compensator gains
K_m = feedforward gains on x_m
K_{mD} = feedforward gains on $\dot{x}_m$
K_p = feedback gains
K_{p0} = initial value of feedback gain matrix
R, Q = weighting matrices of the performance index
u = a vector representation of the simulator control variables
v = variable parameter of the simulator
W = performance index
x = a vector representation of the simulator response variables
x_i = ith response variable
$\partial F/\partial v$ = the partial derivative of the elements of the F matrix with respect to v
$\partial G/\partial v$ = the partial derivative of elements of the G matrix with respect to v
$\partial x/\partial v$ = sensitivity of x vector with respect to a variation in v
δ_j = deflection of the jth control surface
δ_j/e_{xi} = the feedback gain between the control surface δ_j and the error signal e_{xi}
δ_j/x_{i_m} = the feedforward gain between the control surface, δ_j, and the model response variable x_{i_m}
δ/ε_{k_g} = the gust compensator gain between the control surface δ_j and the gust excitation ε_{k_g}
δ_y = side force surface deflection
δ_z = direct lift flap surface deflection
ε = a vector representation of gust excitations
ε_{k_g} = the kth gust signal
ζ = the damping of a second-order system
ω_n = the natural frequency of a second-order system

Superscripts

T = transpose
-1 = matrix inverse

Subscripts

g = gust
I = inertial signal
m = model
ps = variable at TIFS pilot's station
TCG = variable at TIFS center of gravity
C = control command signal

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Introduction

THE theoretical development and flight-test results of the model-following flight control system for the Air Force Total In-Flight Simulator (AF/TIFS)[1], shown in Fig. 1, are presented in this paper. The TIFS airplane is a Convair C-131 modified to obtain independent control of all six degrees of freedom of motion of the vehicle. In addition to the usual pitching, rolling and yawing moment control with the elevator, aileron and rudder, the airplane has been modified to provide for variable thrust, variable side forces by the addition of movable surfaces mounted on and normal to the wings, and variable lift forces through the use of direct left flaps. Control of axial forces is obtained through an electromechanical servo which varies the thrust of the turboprop engines. Each of the other force and moment producing devices is driven by an electrohydraulic servo and the airplane, when configured as a flight simulator, is flown "by wire." A second cockpit, in addition to the normal C-131 cockpit, has been attached to the nose of the airplane. The purpose of this added cockpit is to guarantee the realistic simulation of the pilot's immediate physical surroundings, such as cockpit visibility, displays, and controls having proper feel characteristics.

The TIFS model-following system is unique in comparison to previous systems. The design concept used in the past was based upon using high-error feedback gains between the model and simulator so that the simulator approximated a

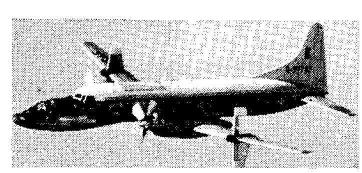

Fig. 1. USAF total in-flight simulator.

unity transfer function system over the frequencies of interest. The magnitude of feedback gains required for good model following is often unrealistic due to servo dynamics, sensor noise, etc. In contrast, the TIFS control deflections which are required for model following are computed primarily by the feedforward gains between the model and TIFS. The feedback gains are used for the purpose of reducing the sensitivity of the model-following system to parameter variations and reducing the model-following errors after the control system is simplified and mechanized. Good model following at one flight condition can be obtained with no feedback at all, but without feedback, the complexity of the system would increase (the system could be not simplified very much) and the quality of model following would deteriorate rapidly as the flight conditions changed.

The paper begins with a general discussion of the objectives and conceptual design of the TIFS model-following system. A more detailed theoretical development which leads to the determination of the system configuration then follows. Consideration is given to the design of the feedforward, gust compensator and feedback gain systems which comprise the TIFS model-following system and the techniques by means of which these gains are computed. Results, in the form of overlays of the model and TIFS time histories, are presented to show the quality of model following obtained from a digital simulation of the final system. Flight-test data are then given to show the quality of model following actually achieved in flight. Lateral-directional and longitudinal responses are shown which substantiate the theory and the design procedure used to obtain the TIFS model-following control system.

Conceptual Design of the TIFS Model-Following System

The objective of the TIFS system is to duplicate the flight path, transients, attitudes and control system characteristics of large aircraft in both a smooth and turbulent environment. Of particular interest is the accurate reproduction of the model's lateral and vertical accelerations at the evaluation pilot's station. These objectives are to be achieved by the model-following control system. In addition, a correct environment for the evaluation pilot is provided by the addition of a second cockpit, so that the cockpit and outside visual references are representative of the vehicle being simulated.

Because it was desired that the model and TIFS responses be identical at the evaluation pilot's station, the pilot's station of the model and the TIFS were assumed to be coincidental. This implied that the model c.g. and TIFS c.g. were not co-located. Therefore, a transformation of the model equations of motion from the model c.g. to the TIFS c.g. was necessary to provide a common reference and a guarantee a dynamic match at the TIFS evaluation pilot's station.

Figure 2 is a block diagram showing the final configuration of the TIFS model-following system which evolved from the theoretical investigations. Three distinct sets of gains are required: 1) Feedforward gains K_m and K_{m_D} which yield theoretically exact model following. These gains are independent of the model dynamics and the command or turbulence inputs; 2) Gust compensator gains K_g which are only a function of the dynamic characteristics of the TIFS. Gust signals, when amplified by the gains K_g, drive the controls so as to counteract the forces and moments produced on TIFS by turbulence and result in theoretically exact gust alleviation; and 3) Feedback gains K_p to minimize the dynamic sensitivity of the system to changes in flight condition of the vehicle. This enables the vehicle to fly over a relatively wide flight range without the need to program the feedforward gains in order to maintain accurate model following. In addition, the feedback loops lessen the effect of unknown or inaccurately identified dynamic characteristics of the TIFS vehicle.

It was felt that a system with constant gains would result in satisfactorily accurate model following over the entire landing approach "island" of operation. The constant gain system was determined by first choosing a nominal flight condition within the required terminal area "island" of operation. Feedforward and gust compensator gains to give theoretically exact model following and gust alleviation at this flight condition were then calculated. The constant feedback gains were then chosen to minimize the dynamic sensitivity of the model-following system to changes in flight condition throughout the landing approach "island."

Design of the Model-Following Control System

This section is devoted to a discussion of the design techniques used to obtain the system gains just discussed. Consider first the feedforward gains which are chosen to give theoretically exact model following at a nominal flight condition in the landing approach island. Let the linearized, small perturbation equation of motion for the model be represented in the general form

$$\dot{x}_m = F_m x_m + G_m u_m \tag{1}$$

The linearized, small perturbation motion representation of the TIFS aircraft is the same form as the model but without subscript, i.e.,

$$\dot{x} = Fx + Gu \tag{2}$$

The control law that will theoretically force the TIFS to respond as the model is given by

$$u = K_{m_D}\dot{x}_m + K_m x_m - K_p x \tag{3}$$

$$= (G^T G)^{-1} G^T [\dot{x}_m - (F - GK_p) x_m] - K_p x \tag{4}$$

K_{mD} and K_m are obtained by substituting Eq. (3) into Eq. (2), letting $x = x_m$ and $\dot{x} = \dot{x}_m$ as desired, and equating like coefficients. This equation reveals that accurate model following depends directly upon a knowledge of the stability and control derivatives of only the TIFS airplane. The control system design just described is unique in its computational simplicity. The determination of the feedforward gains for any feedback configuration require only matrix

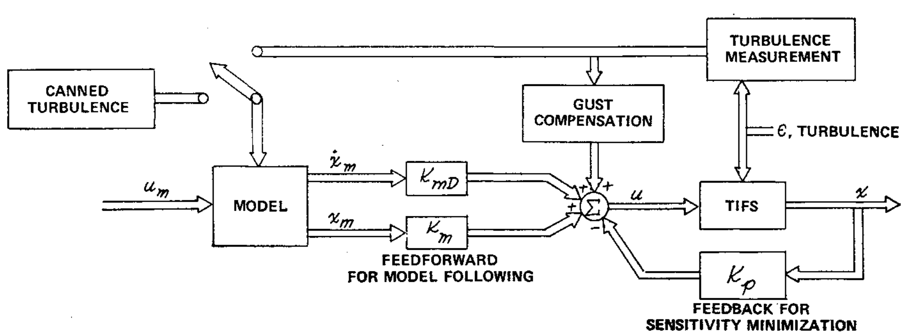

Fig. 2 Block diagram of TIFS control system.

algebra computational routines. It has also been found that many of the individual elements of the gain matrices can be eliminated, with negligibly small effect on the model-following capability of the system, thus simplifying the actual implementation on the TIFS computers. The TIFS flight-test results have proven that the estimates of the stability and control derivatives of the base airplane which are available from wind-tunnel testing, engineering calculations, etc. are sufficient for use in determining the feedforward gains which lead to good model following. Of course, the more accurately these derivatives are known the better the quality of model following.

Several assumptions are inherent in the derivation of the equations for the feedforward gains required for the TIFS responses to perfectly match those of the model. For instance, it is assumed that the linear, small perturbation representation of both the TIFS and model is valid. Furthermore, the effect of the actuators and sensor dynamics has been neglected. Experience has shown that this is a valid assumption if the actuator bandwidth is about three times greater than the frequencies present in the model and TIFS dynamic responses. The fact that six independent controls exist on TIFS, one for each force and moment, also allows the TIFS responses to exactly match those of the model. This is not true when a conventional aircraft, with only four controllers, is used for the simulator.

Turbulence Simulation and Alleviation

In addition to model following and sensitivity reduction, another goal of the TIFS flight control system is to guarantee that the TIFS airplane responds appropriately to turbulence, either existing atmospheric or artificially generated turbulence. Proper model following in the presence of atmospheric turbulence requires gust alleviation of the TIFS airplanes, measurement of the turbulence field, and proper insertion of the measured turbulence into the model computer.

The feedback gains, although designed for sensitivity minimization, do, by their very presence, produce some gust alleviation. In addition, the gust compensator has the effect of reducing the vehicle perturbations even more. This compensation is designed as follows.

The TIFS equations of motion are assumed to be of the form

$$\dot{x} = Fx + Gu + J\varepsilon \tag{5}$$

The gust compensation is defined by

$$u = -(G^TG)^{-1}GJ\varepsilon \tag{6}$$

which comes about by requiring that the excitation to the TIFS equations of motion be zero, i.e.,

$$Gu + J\varepsilon = 0 \tag{7}$$

All of the assumptions made in the derivation of the equation for exact model following are also inherent in the derivation of this equation for exact gust alleviation. They are: 1) The linear, small perturbation equations of motion are assumed to be valid; 2) Independent control of all six degrees of freedom is necessary to provide exact gust alleviation; and 3) Accurate knowledge of the TIFS vehicle control and turbulence effectiveness derivatives is necessary.

Furthermore, this solution is only a first approximation to the exact gust alleviation solution since the effects of finite actuator bandwidth have been neglected. In practice, the frequency responses of the servos limit the spectrum which can be alleviated since the rates at which the controllers can move is limited. The aircraft response to gusts at frequencies lower than the servo bandwidths are alleviated while higher frequencies may actually be amplified. With regard to turbulence simulation, it is felt the combination of matching the low-frequency gust responses of the model and the high-frequency turbulence responses of the aircraft, which cannot be eliminated nor simulated, will provide a response spectrum which is not drastically different from the actual total turbulence response of the model vehicle.

Sensitivity Minimization of the Model-Following System and Feedback Gain Design

The feedback gains of the model-following system were chosen to minimize sensitivity and enable the TIFS vehicle to fly over as wide a range of conditions as possible without a gain scheduling requirement. The determination of these gains is complicated by the fact that sensor noise, structural modes, etc., limit their magnitude in practical situations. Furthermore, it was felt that constant gains rather than gains programed as a function of flight condition would produce adequate model following over the terminal area operation "island."

Two different design approaches were developed to obtain the feedback gains, one each for the lateral-directional and longitudinal modes of motion of the vehicle. The longitudinal design procedure has already been published in Ref. (2) and is not repeated here.

The lateral-directional feedback gain system was determined by using a sensitivity minimization approach. In this approach, an initial set of feedback gains K_{p0} is assumed. The feedforward gains are computed by Eq. (4). A perturbation to this original gain matrix ΔK is then computed which results in lower system sensitivity. A new value of K_p and the corresponding feedforward gains are obtained. An iterative procedure is then followed to obtain a set of feedback gains within realizable magnitude limitations and a corresponding set of feedforward gains. The following performance index was formulated to reflect the desire to minimize the sensitivity of the TIFS response variables to a variation in a parameter v:

$$W = \int_0^\infty \{(\partial x/\partial v)^T Q(\partial x/\partial v) + \bar{x}^T R\bar{x}\}dt \tag{8}$$

where

$$\bar{x}^T = [x^T, x_m{}^T, u_m{}^T] \tag{9}$$

This performance index is constrained by the sensitivity equations of the model-following system which can be shown to be

$$\partial\dot{x}/\partial v = (F - GK_{p0})(\partial x/\partial v) + A\bar{x} \tag{10}$$

where

$$A = [(\partial F/\partial v) - (\partial G/\partial v)(K_{p0}), \\ -(\partial G/\partial v)(K_m + K_{mD}F_m), (\partial G/\partial v)K_{mD}G_m] \tag{11}$$

The optimum control law is well known and given by

$$\bar{x} = -R^{-1}A^TP(\partial x/\partial v) \tag{12}$$

where P is the positive definite solution of the Riccati equation

$$P(F - GK_{p0}) + (F - GK_{p0})^TP - PAR^{-1}A^TP + Q = 0 \tag{13}$$

More explicitly, the control law is of the form

$$\begin{bmatrix} x \\ x_m \\ u_m \end{bmatrix} = -\begin{bmatrix} K_{p1} \\ K_{p2} \\ K_{p3} \end{bmatrix} (\partial x/\partial v) \tag{14}$$

where K_{p1}, K_{p2} and K_{p3} are partitioned submatrices of the $R^{-1}A^TP$ term of Equation (12). Substituting Eq. (14) and

(11) into Eq. (10) results in a closed-loop regulator for the sensitivity vector equations whose motions are defined by

$$\frac{\partial \dot{x}}{\partial v} = \left[(F - GK_{p0}) - \left(\frac{\partial F}{\partial v} - \frac{\partial G}{\partial v} K_{p0}\right) K_{p1} + \frac{\partial G}{\partial v}(K_m + K_{m_D}F_m)K_{p2} + \frac{\partial G}{\partial v} K_{m_D}G_m K_{p3}\right]\frac{\partial x}{\partial v} \quad (15)$$

The results of the previous analysis required a generation of the sensitivity equations and an implementation of the control law given by Eq. (14). However, this is not desirable because of the complexity of generating $\partial x/\partial v$ and not feasible because x_m and u_m are not free variables.

An alternative technique for using the results of the previous approach to achieve a lower system sensitivity and which is consistent with the idea of using just the feedback gains for sensitivity minimization is now discussed. Let ΔK denote a perturbation to the initial feedback gain matrix K_{p0}. The objective is to determine a ΔK which results in lower system sensitivity. For the feedback gains $K_{p0} + \Delta K$ the sensitivity equations of the model-following system are

$$\frac{\partial \dot{x}}{\partial v} = [F - G(K_{p0} + \Delta K)]\frac{\partial x}{\partial v} + \left[\frac{\partial F}{\partial v} - \frac{\partial G}{\partial v}(K_{p0} + \Delta K)\right] x - \frac{\partial G}{\partial v}(K_m + K_{m_D}F_m)x_m - \frac{\partial G}{\partial v} K_{m_D}G_m u_m \quad (16)$$

It is desired to have Eq. (16) reflect the results of Eq. (15) by just a change in the initial feedback gains ΔK. A comparison of these two equations reveals that no value of ΔK exists which will make them identical. As a compromise it was decided to find the ΔK which equates the sensitivity portion of the two equations, i.e.,

$$[F - G(K_{p0} + \Delta K)]\frac{\partial x}{\partial v} = \left\{(F - GK_{p0}) - \left[\frac{\partial F}{\partial v} - \frac{\partial G}{\partial v} K_{p0}\right] K_{p1} + \frac{\partial G}{\partial v}(K_m + K_{m_D}F_m)K_{p2} + \frac{\partial G}{\partial v} K_{m_D}G_m K_{p3}\right\}\frac{\partial x}{\partial v} \quad (17)$$

Equating coefficients and solving for ΔK results in

$$\Delta K = (G^T G)^{-1} G^T \left\{\left(\frac{\partial F}{\partial v} - \frac{\partial G}{\partial v} K_{p0}\right) K_{p1} - \frac{\partial G}{\partial v}(K_m + K_{m_D}F_m)K_{p2} - \frac{\partial G}{\partial v} K_{m_D}G_m K_{p3}\right\} \quad (18)$$

The initial feedback gain matrix is then changed by this quantity in an attempt to arrive at a system with lower sensitivity to parameter variations. Gains within prescribed magnitudes are easily obtained by properly selecting Q and R. Digital simulation results showing the quality of model following obtained with the system resulting from this approach are given in a later section.

Control Law Simplifications

This section contains the general form of the control law of the TIFS model-following system. This system of gains is that which resulted after simplification of the theoretical gain system. Many gain elements contributed relatively little to the performance of the system and were eliminated with negligible loss in performance. Furthermore, when the model-following configuration was mechanized, the following modification to the form of the control law, obtained by expanding Eq. (4), was made to obtain direct error feedback

$$u = (G^T G)^{-1} G^T \dot{x}_m - (G^T G)^{-1} G^T F x_m + K_p(x_m - x_p) \quad (19)$$

This modification produced mechanization conveniences that made it easier to set up the flight-test program and analyze the results.

The control law for the longitudinal mode of TIFS model-following operation is

$$\begin{bmatrix}\delta_{e_c}\\ \delta_{x_c}\\ \delta_{z_c}\end{bmatrix} = \begin{bmatrix}\delta_e/e_q & \delta_e/e_\theta & \delta_e/\int e_\theta & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & \delta_x/e_{\dot{V}} & \delta_x/e_{\Delta V} & \delta_x/\int \Delta V & 0 & 0\\ \delta_z/e_q & 0 & 0 & 0 & 0 & 0 & \delta_z/e_{\Delta\alpha} & \delta_z/\int e_{\Delta\alpha}\end{bmatrix}\begin{bmatrix}e_q\\ e_\theta\\ \int e_\theta\\ e_{\dot{V}}\\ e_{\Delta V}\\ \int e_{\Delta V}\\ e_{\Delta\alpha}\\ \int e_{\Delta\alpha}\end{bmatrix}$$

$$+\begin{bmatrix}\delta_e/\dot{q}_m & 0 & \delta_e/\dot{V}_{mTCG} & 0 & 0\\ 0 & 0 & \delta_x/\dot{V}_{mTCG} & 0 & 0\\ 0 & \delta_z/q_m & 0 & \delta_z/\dot{\alpha}_{mTCG} & \delta_z/\Delta\alpha_{mTCG}\end{bmatrix}\begin{bmatrix}\dot{q}_m\\ q_m\\ \dot{V}_{mTCG}\\ \dot{\alpha}_{mTCG}\\ \Delta\alpha_{mTCG}\end{bmatrix} + \begin{bmatrix}0\\ \delta_x/\alpha_g\\ \delta_z/\alpha_g\end{bmatrix}\alpha_g$$

Similarly, the lateral-directional control law is

$$\begin{bmatrix}\delta_{a_c}\\ \delta_{r_c}\\ \delta_{y_c}\end{bmatrix} = \begin{bmatrix}\delta_a/e_p & \delta_a/e_\phi & 0 & 0 & 0 & 0\\ 0 & 0 & \delta_r/e_r & \delta_r/\sin e_\psi & \delta_r/e_\beta & \delta_r/\int e_\beta\\ 0 & 0 & 0 & 0 & \delta_y/e_\beta & \delta_y/\int e_\beta\end{bmatrix}\begin{bmatrix}e_p\\ e_\phi\\ e_r\\ \sin e_\psi\\ e_\beta\\ \int e_\beta\end{bmatrix}$$

$$+\begin{bmatrix}\delta_a/\dot{p}_m & \delta_a/p_m & 0 & 0 & 0 & 0 & \delta_a/\beta_{mTCG} & 0\\ 0 & \delta_r/p_m & \delta_r/\phi_m & \delta_r/\dot{r}_m & \delta_r/r_m & \delta_r/\dot{\beta}_{mTCG} & \delta_r/\beta_{mTCG} & 0\\ 0 & \delta_y/p_m & 0 & \delta_y/\dot{r}_m & 0 & 0 & \delta_y/\beta_{mTCG} & \delta_y/n_{y_{mTCG}}\end{bmatrix}\begin{bmatrix}\dot{p}_m\\ p_m\\ \phi_m\\ \dot{r}_m\\ r_m\\ \dot{\beta}_{mTCG}\\ \beta_{mTCG}\\ n_{y_{mTCG}}\end{bmatrix} + \begin{bmatrix}\delta_a/\beta_g\\ \delta_r/\beta_g\\ \delta_y/\beta_g\end{bmatrix}\beta_g$$

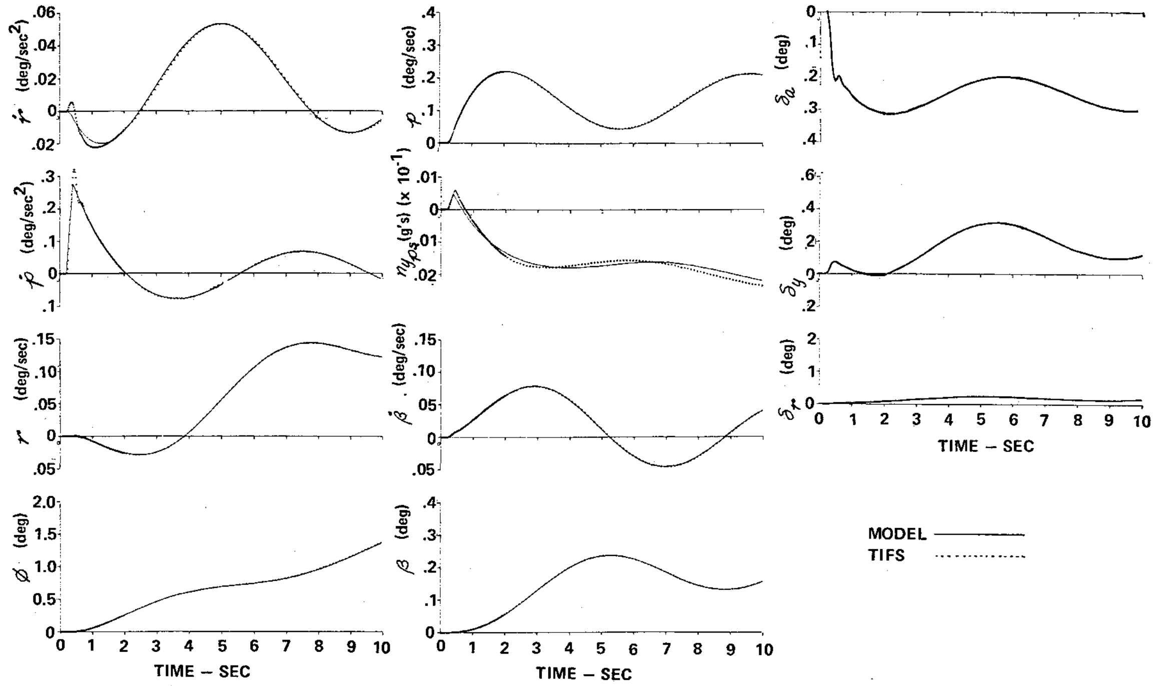

Fig. 3 Digital simulation model-following results; nominal flight condition; minimum sensitivity feedback gains $\delta_{wheel_m} = 1$ degree step.

Digital Simulation Results

An evaluation of the AF/TIFS model-following system using a digital simulation was undertaken prior to flight test in order to ascertain the quality of model following achievable with the system designed using the techniques presented previously. The simulation was as realistic of the in-flight system as feasibly possible. The model and TIFS included nonlinear aerodynamics and kinematics. In addition, the dynamics of the actuators were accounted for in the simulation and modeled as linear, second-order systems. One intent of performing the simulation was to determine what effects these nonlinearities and dynamics would have on the quality of model following for a control system designed by neglecting these effects. Another intent was to ascertain the effects of the simplification of the control law achieved by the elimination of gains which were felt to have a negligible effect on the operation of the system. Most importantly the simulation was used to assess the performance of the model-following system at different flight conditions in the landing approach "island," i.e., the sensitivity of the model-following system.

Figures 3, 4, and 5 contain results of the digital simulation for the TIFS model following a representation of a conventional jet transport. They are included to justify the theory and techniques developed in the previous sections. The responses shown are for a 1° wheel step into the model. Figure 3 shows the results for the nominal flight condition chosen for the landing approach island which was at an altitude of 5,000 ft and a speed of 273 fps. Included are overlays of the accelerations, velocities and position variables of both the

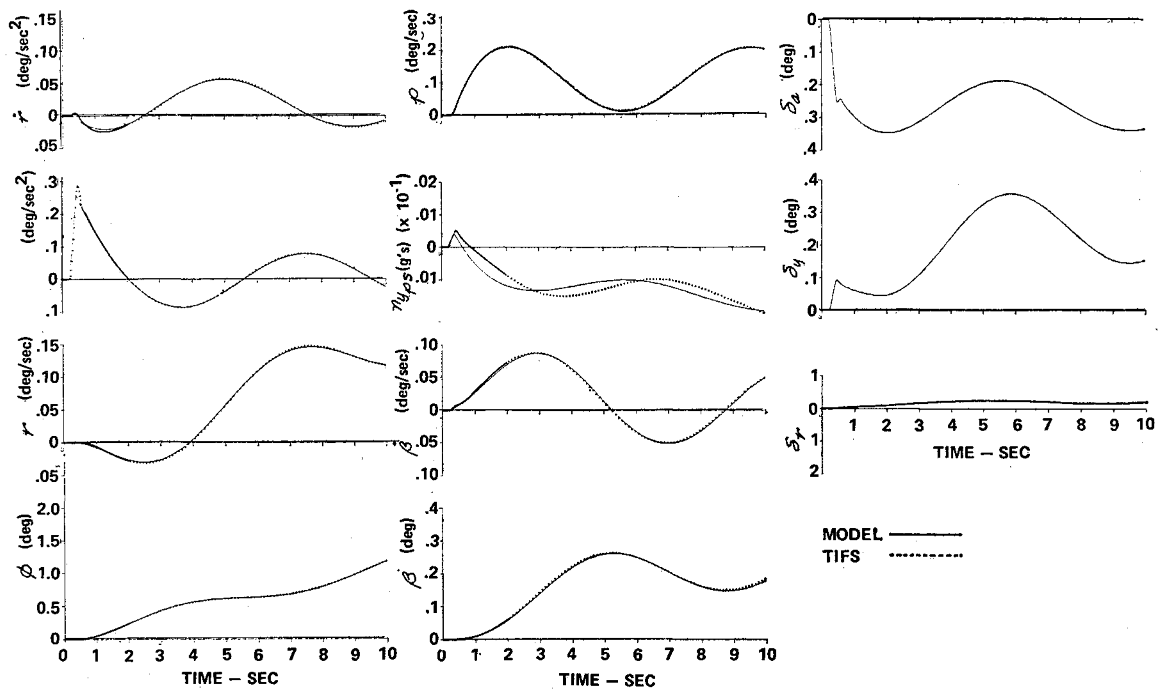

Fig. 4 Digital simulation model-following results; off-nominal flight condition; minimum sensitivity feedback gains $\delta_{wheel_m} = 1$ degree step.

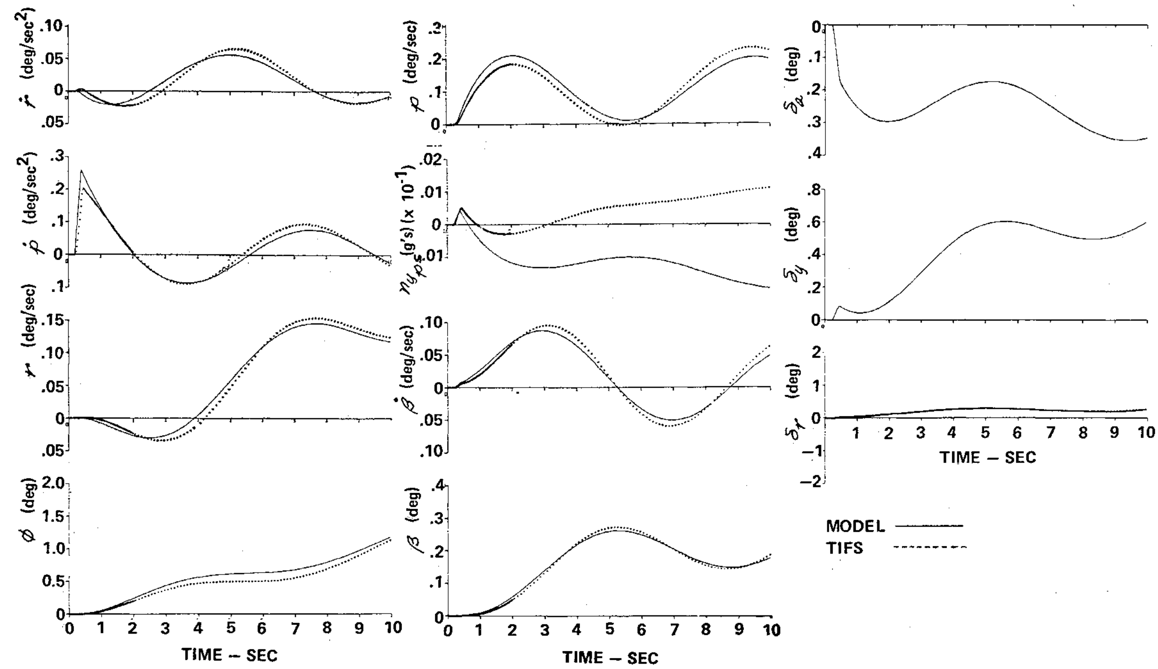

Fig. 5 Digital simulation model-following results; off-nominal flight condition — initial feedback gains $\delta_{wheel_{1m}} = 1$ degree step.

model and TIFS. The model responses are the solid lines while the TIFS responses are dotted. Control deflections are also given.

Figure 4 shows similar results for an off-nominal flight condition using the final feedback gain system developed. This off-nominal flight condition was at an altitude of 3,000 ft and speed of 228 fps. Figure 5 is included to make clear the improvement in the model-following system response obtained at this off-nominal condition using the results of the sensitivity minimization approach developed previously. The feedback gain matrix used for this figure was the initial one used for the development of the gains by the sensitivity minimization approach. It consisted of just $\delta_r/\sin e_\psi$ and $\delta_y/\int e_\beta$. It was desired to choose a K_{po} as close to the null matrix as possible and let the computer optimization program determine the final K_p required. The initial set of feedback gains was chosen to satisfy computational requirements of the approach. It is felt that the theory and design procedure used to obtain the feedback gains of the model-following system was very effective.

The intent of the design was to produce a control system that would force the TIFS airplane to respond as the model responds in all the variables of the model; $\dot{V}_{mTCG}$, $\dot{\alpha}_{mTCG}$, $\dot{\beta}_{mTCG}$, $\dot{p}_m$, $\dot{q}_m$, $\dot{r}_m$, $n_{y_{mps}}$ $n_{x_{mps}}$, $n_{z_{mps}}$, p_m, q_m, r_m, Δh_m, ϕ_m, θ_m and $\Delta\psi_m$. As shown in the figures, $n_{y_{mps}}$ was the most difficult variable to reproduce under the restriction that all the other variables must also follow the model. The digital simulation was a nonlinear one using a control law based upon a linearized representation of TIFS. A linear simulation (not shown) yielded exact model following at the nominal flight condition and of course, $n_{y_{mps}}$ following was exact also. In actual flight, the lateral acceleration response of the TIFS airplane accurately reproduced the $n_{y_{ps}}$. response of the model (see Fig. 6) indicating that the airplane itself is more linear than its wind-tunnel representation.

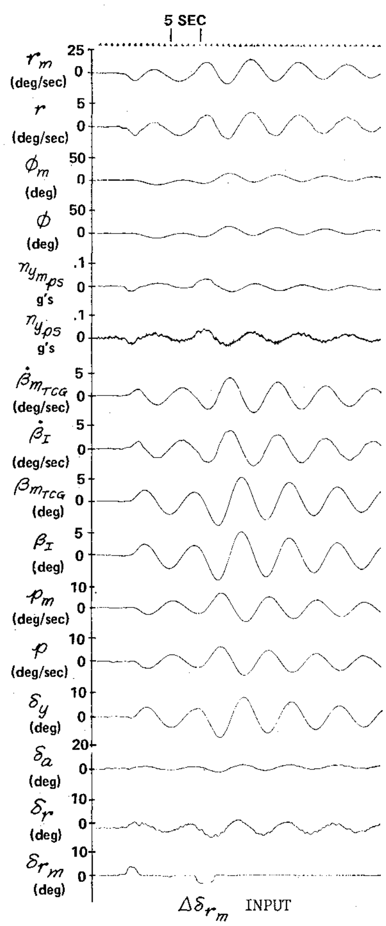

Fig. 6 TIFS lateral-directional model-following; flight-test records.

Flight-Test Results

Results of the TIFS flight test showing the model-following capability of the system are given in Figs. 6 and 7. Both longitudinal and lateral-directional responses are given. The model was the same one used in the digital simulation. These responses were obtained at a true airspeed of 290 fps and an altitude of 10,000 ft. This differed slightly from the design flight condition and was used so that the system could be checked out in a nonturbulent environment. Included in these figures are the model responses followed by the corresponding responses of the model-following system. Control deflections are also given. For the longitudinal cases, the

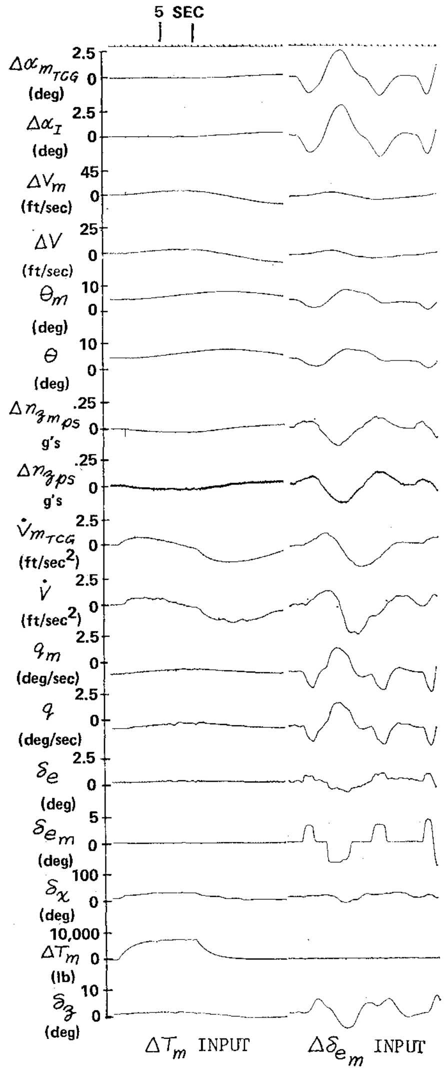

Fig. 7 TIFS longitudinal model-following; flight-test results.

model inputs were a throttle step and a series of elevator doublets. In the lateral-directional case, rudder pulse inputs were used.

It is felt that the flight-test results of TIFS substantiate the theory and design procedure used to obtain the gains. However, some errors in model following are evident upon careful scrutiny of the flight-test records which do not appear on the responses of the digital simulation. Efforts are currently underway to rectify this. There are several sources for these errors, including:

1) The elevator and rudder actuators had a lower frequency response than anticipated, 2 Hz and 3.5 Hz, respectively, instead of the 6 Hz that was programed into the digital simulation. In addition, the actual engine thrust response was different from the assumed response. Originally, the thrust response was modeled as a second-order system with $\omega_n = 14$ rad/sec and $\zeta = 0.5$ while flight-test data indicated that these parameters were $\omega_n = 2.25$ rad/sec and $\zeta = 0.75$.

2) Some of the feedback gains could not be made as large as desired due to such things as sensor noise. This was desirable to lessen system sensitivity.

3) The TIFS stability and control derivatives determined from wind-tunnel data were used to calculate the feedforward and gust compensator gains. These gains were not updated based on identification of the TIFS derivatives from flight-test data.

4) The air data measurement system may have introduced model-following errors due to either noise on the signals or the dynamics of filters present in it. In addition, some variables were obtained by solving a simplified set of the equations of motion which may have introduced additional error. Last of all, it was found that the pressure sources on the TIFS were affected by the airflow from the propellers under certain conditions causing some computed TIFS response variables to be in error.

Conclusions

This paper has included the theoretical development and flight-test results of the model-following control system of the Air Force Total In-Flight Simulator. A discussion of the conceptual design and detailed theoretical development of the control system was given. It was shown that the feedforward and gust compensator gains were obtained by simple matrix calculations. The procedure used to obtain the lateral-directional feedback gains for sensitivity minimization was developed and verified by digital simulation results. The final general form of the control law was also presented. Time histories of the model and TIFS responses from flight test were also included to show the quality of model following obtainable with the system. These records substantiate the theory and design procedure used to obtain the flight control configuration for the TIFS model-following system.

References

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