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# Pilot-in-the-Loop Analysis of Propulsive-Only Flight Control Systems

by


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## ABSTRACT

Longitudinal control system architectures are presented which directly couple flight stick motions to throttle commands for a multi-engine aircraft. This coupling enables positive attitude control with complete failure of the flight control system. The architectures chosen vary from simple feedback gains to classical lead-lag compensators with and without prefilters. Each architecture is reviewed for its appropriateness for piloted flight. The control systems are then analyzed with pilot-in-the-loop metrics related to bandwidth required for landing. Results indicate that current and proposed bandwidth requirements should be modified for throttles only flight control. Pilot ratings consistently showed better ratings than predicted by analysis. Recommendations are made for more robust design and implementation. The use of Quantitative Feecback Threory for compensator design is discussed. Although simple and effective augmented control can be achieved in a wide variety of failed configurations, a few configuration characteristics are dominant for pilot-in-the-loop control. These characteristics will be tested in a simulator study involving failed flight controls for a multi-engine aircraft.


## NOTATION

| | |
|---|---|
| $q$ | pitch rate (deg/sec) |
| $\alpha$ | perturbed angle of attack (deg) |
| $u$ | perturbed velocity (ft/sec) |
| $\theta$ | perturbed pitch angle (deg) |
| $h$ | altitude change-down (ft) |
| $\gamma$ | perturbed flight path angle (deg) |
| $\Gamma$ | glide slope deviation angle (deg) |
| $G_{in}^{out}$ | transfer function (s) |
| (a) | short form for (s+a) |
| $(\zeta, \omega_n)$ | short form for $s^2 + 2\zeta\omega_n s + \omega_n^2$ |
| $K_q$ | pitch rate feedback gain |
| $K_\gamma$ | gamma loop feed back gain |
| $\delta_{Tc}$ | throttle command (%) |
| z | thrust (lbs) |
| $\delta_s$ | stick input (full deflection=1 unit) |
| P | quadruple state-space representation |
| $M_u$ | dimensional speed derivative |
| $M_\alpha$ | static stability dimensional derivative |

## INTRODUCTION

Work at NASA Dryden has shown that compensated thrust modulation coupled to flight stick motion provides a positive degree of flight controllability in the event of complete failure of the flight control system. Feedback control laws developed empirically had dramatically improved the pilot ratings from Level 3 to Level 2 for the simulated approach and landing of a Boeing 720 with failed flight controls[1-3] . Initial work on the modeling of these control systems showed that relatively simple feedback architectures, as well as those based on optimal control theory, could ease the piloting task for throttles-only flight unless moderate turbulence was encountered.[4-5]

The main thrust of research reported here has been to investigate the effect of throttles-only flight control on the flying qualities of multi-engine aircraft. Analytical system surveys are accomplished to explain this improvement from a handling qualities point of view. The pilot-in-the-loop metrics used in the investigation are primarily related to bandwidth criteria as reported in the literature. [6]

Previous work was extended by developing classical compensator designs with and without prefiltering to further improve the piloted ratings. The design goal was to find a robust controller for throttle-only control under various approach and landing flight conditions. Designs obtained from optimal control theory showed performance sensitivity to configuration changes[5].

All work assumes that the aircraft configuration has a positive $M_u$ dimensional derivative and positive stability ($M_\alpha < 0$). System surveys follow, then the design architectures are analyzed. An expanded Appendix describes the aircraft configurations.

## THROTTLES-ONLY SYSTEM SURVEYS

The basic system model as shown in the Appendix has four variations of configuration. The engine and bare airframe state-space models, called quadruples[7], were derived from perturbations of the full non-linear equations of motion about trim. Transfer functions used in design were then approximated with low order fits over the frequency range of effective throttle control.

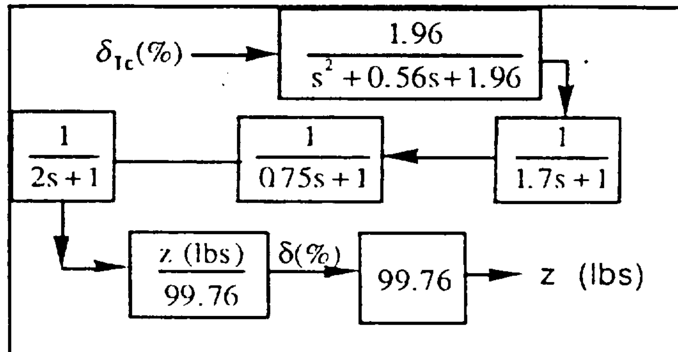


Figure 1 Engine Spooling Block Diagrams

**Engines**. The spool-up and spool-down engine dynamics for the B-720 engine are shown in Figure 1. The empirical transfer function developed is given in short form notation by

$$G^{z(lbs)}_{\delta_{Tc}(\%)} = \frac{275}{(0.55)(5)}$$

The above equation is illustrated in Fig. 2 over low frequency ranges up to 1.0 rad/sec.

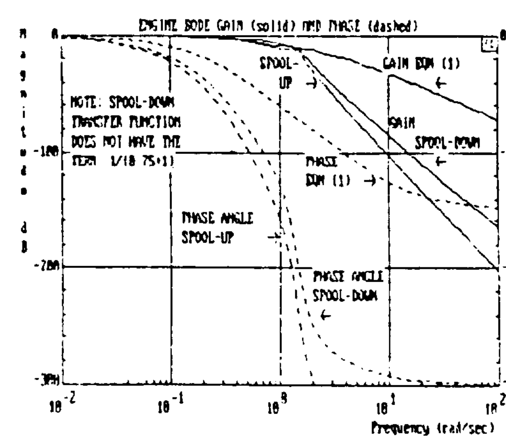


Figure 2 Engine $\delta$ to $\delta_{Tc}$

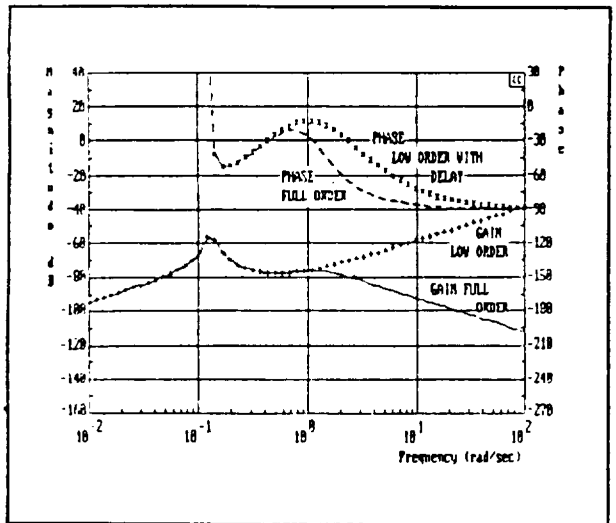

Figure 3 Pitch Rate to Thrust Bode

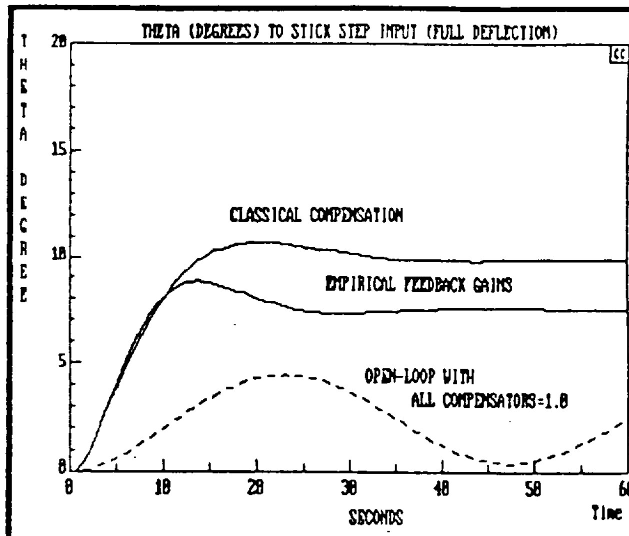

Figure 4 Longitudinal Time Responses

Bare Airframe. It is apparent from the engine bode diagrams that severe bandwidth attenuation occurs beyond frequencies of 1 rad/sec. It may not be possible, therefore, to increase the closed-loop bandwidth beyond 1 rad/sec within the range of available thrust.

This can be seen in the pitch rate "q" to thrust "z" transfer function of the bare airframe shown in Figure 3. The full-order thansfer function $G^{q(deg/sec)}_{z(lbs)}$ shows that 80 db of gain must be added to yield a crossover frequency beyond 1 rad/sec. This corresponds to 10,000 lbs of full thrust from each engine, which would not be practical for approach and landing.

A low order fit to $G^{q(deg/sec)}_{z(lbs)}$ is also depicted in Figure 3 and is very accurate near the phugoid frequency. Piloted flight of the unaugmented aircraft was consistently Level 3. The main difficulties were the lightly damped phugoid and the low bandwidth throttle control. The open-loop response of pitch angle to a full deflection step stick input is shown in Figure 4 with all compensation set to unity (see Appendix).

The accuracy of the low order fit near the phugoid frequency means that, to a first order approximation[9], the phugoid frequency and damping are found from

$$2\zeta\omega_n = -X_u + \frac{M_u(X_\alpha - g)}{M_\alpha}$$

$$\omega_n^2 = \frac{-g(Z_u - \frac{M_u}{M_\alpha}Z_\alpha)}{U_o}$$

and for conventional transport aircraft can be shown to be roughly proportional to $M_u$.

It should be strongly noted here for the classic case of $M_u$=0 and for negative values of $M_u$ (Mach tuck) that the aircraft cannot be practically flown with throttles alone unless rotational control in pitch is added. Difficulties will also be encountered as $M_\alpha$ becomes small (aft cg location). Both of these cases require the addition of an effective rotational controller about the pitch axis. This may be achieved using differential inboard and outboard thrust, provided the inboard engines are a different distance from the aircraft xy-plane than the outboard engines. These configuration characteristics determine the innate capability for throttles-only piloted control.

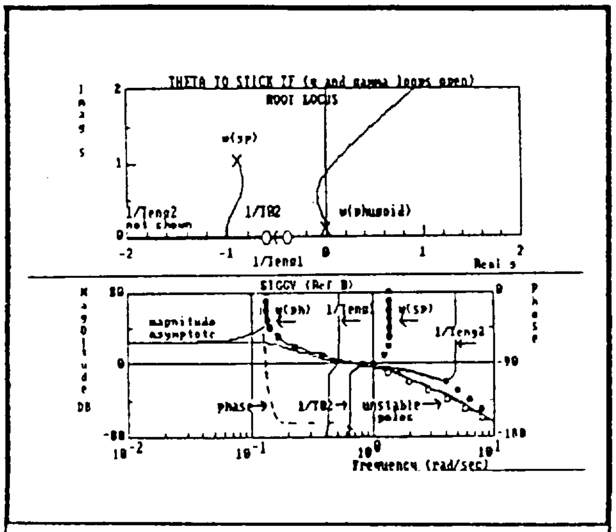


Figure 5 Pitch Angle System Survey

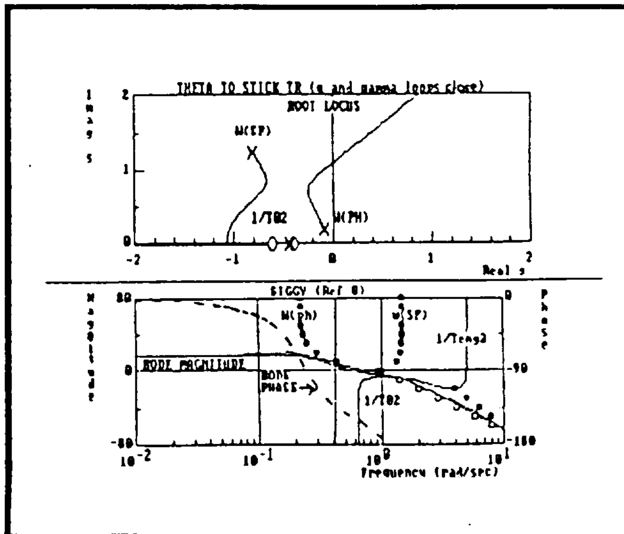


Figure 6 Survey with Empirical Feedback

## FEEDBACK ARCHITECTURES

The generic feedback architecture is given in the Appendix. An effort was made in the designs to keep the structure simple, and so in all cases the flight path compensation was unity. The open-loop pitch angle to stick root locus, Bode, and "Siggy" plots[8] are shown in Figure 5. They are characterized by excessive resonance at $\omega_{nph}$, low phase and gain margins, low crossover frequency, and large phase angle roll-off. The open-loop (OL) system is

$$G^{\theta(\deg)}_{\delta_s(\text{units})} \overset{\text{loops}}{\underset{\text{open}}{=}} \frac{8.32(0.4)(0.61)}{(.0039,0.13)(0.65,1.38)(0.55)(5.0)}$$

The root locus of the open-loop system makes it apparent that any feedback is limited by the phugoid roots going unstable.

**Empirical Feedback.** This longitudinal control law was developed by trial and error in the simulator at NASA Dryden with a pilot in the loop. It is given by

$$\{G^{\gamma_{in}(\deg)}_{\delta_s(\text{units})}, G^{\delta_{Tc}(\%)}_{e_\gamma(\deg)}, K_q, K_\gamma, G^{\theta_{in}(\deg)}_{\gamma(\deg)}\} = \{10,10,4,1,1\}$$

The system survey for this structure is shown in Figure 6.

It can be seen that the q and $\gamma$ feedback loops removed the resonance at the phugoid frequency along with the rapid phase drop. The gain and phase margins, however, are still low. The q loop closure caused the increase in phugoid damping, and the $\gamma$ loop closure provided an additional 70% increase in settling time. The empirical feedback essentially cancelled the modified engine mode at -0.397 as shown below.

$$G^{\theta(\deg)}_{\delta_s(\text{units})} \overset{\text{loops}}{\underset{\text{closed}}{=}} \frac{8.42(0.4)(0.61)}{(0.518,0.244)(0.517,1.5)(0.397)(5.16)}$$

**Classical Feedback Design.** Classical compensation was designed to address the low gain and phase margins and to increase system bandwidth within the practical limits of the throttle command. The compensation chosen was

$$\{G^{\gamma_{in}(\deg)}_{\delta_s(\text{units})}, G^{\delta_{Tc}(\%)}_{e_\gamma(\deg)}, K_q, K_\gamma, G^{\theta_{in}(\deg)}_{\gamma(\deg)}\} =$$
$$\{8, 14\frac{(s+0.55)}{(s+0.65)}, 4, \frac{(s+0.65)}{(s+1.3)}, 1\}$$

The survey for this system is similar to Figure 6 and not repeated here.

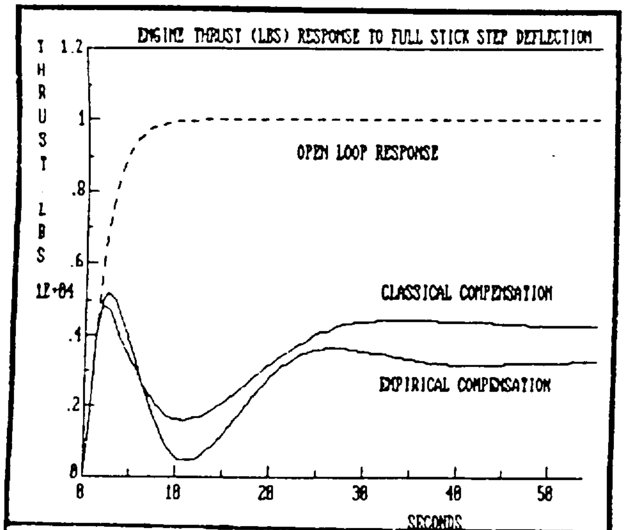


Figure 7 Comparison of Commanded Thrust

The classical design improved the empirical one primarily by increasing the phase margin of the pitch angle to stick transfer function from 13 to 26 degrees. The crossover frequency remained near 0.98 rad/sec.and the steady state performance increased 10%.

The improvement in phase margin made the controller more robust when used to fly the other configurations. The empirical controller was also surprisingly robust when used to fly the other configurations. A complete discussion of this is found in Reference 9.

Further improvements in bandwidth could be achieved only by substantially raising the compensator gain. This resulted in excessive control (thrust). A comparison of the thrust response to a full stick step deflection for the different feedback architectures is given in Figure 7. It was assumed that the throttle command could be moved instantaneously. A throttle actuator would introduce an additional lag.

Compensators currently being designed using Quantitative Feedback Theory are having similar difficulty meeting reasonable limits on control activity when the design closed-loop bandwidth is near 1 rad/sec. A design procedure is being developed to determine the achievable closed-loop bandwidth for a set of configurations given a bandwidth limit on a primary controller.

## CONCLUSIONS

Bandwidth requirements on pitch to stick response should reach 3 rad/sec for acceptable pilot ratings[6]. Augmented throttles-only flight could not reach beyond 1 rad/sec, and received acceptable Level 2 ratings unless moderate turbulence was applied to the simulation. Work in progress at Systems Technology Inc. is establishing bandwidth limits for large, landing aircraft, and these limits will be used to design future compensators. Within the limits set by key configuration variables $M_u$ and $M_\alpha$, simple classical compensators that increase the phase margin result in acceptable pilot ratings for throttles-only flight.

## ACKNOWLEDGMENT

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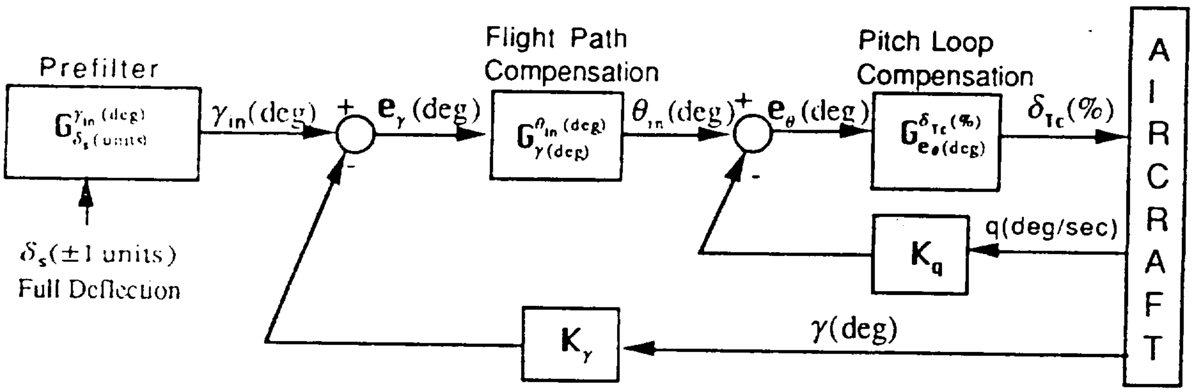
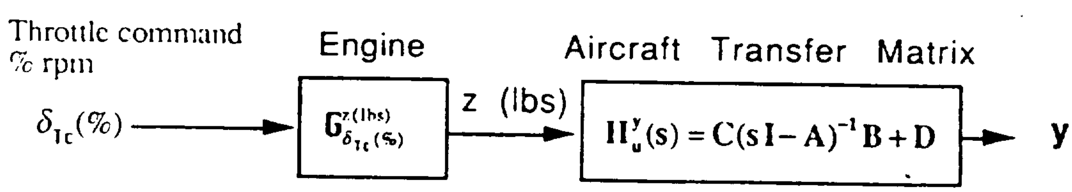
## APPENDIX: B-720 CONFIGURATIONS

The B-720 piloted simulation can be represented by the following block diagram:




The "aircraft" above represents both the engine and the bare airframe dynamics. The engine is approximated by a transfer function and the bare airframe dynamics are represented mathematically by a single quadruple, Pa/c, shown as follows.




$$P_{a/c} = \left[\begin{array}{c|c} A & B \\ \hline C & D \end{array}\right] \overset{\text{throttle inputs equal}}{=} \left[\begin{array}{c|c} A & B_1(\text{column}) \\ \hline C & D=0 \end{array}\right]$$

$$x = [q(\text{deg/sec}) \mid \alpha(\text{deg}) \mid v(\text{kts}) \mid \theta(\text{deg}) \mid h(\text{ft})]^T$$

$$y = [n_{\text{pilot g's}} \mid n_{\text{fcs g's}} \mid q \mid \alpha \mid v \mid \theta \mid h \mid \gamma(\text{deg})]^T$$

The thrust control depends on whether four engines receive independent or identical commands:

$$\mathbf{u} = \left[ z_{\text{outbd left}}(\text{lbs}) \mid z_{\text{inbd left}}(\text{lbs}) \mid z_{\text{inbd right}}(\text{lbs}) \mid z_{\text{outbd right}}(\text{lbs}) \right]^T$$

$$\mathbf{u}_1 = z(\text{lbs}) \qquad \text{[used when all throttles have same command]}$$

Note when all four throttles are given the same command from the pilot stick input the **B** matrix becomes a single column. Each row value in this column matrix $\mathbf{B_1}$ is equal to the sum of the corresponding row elements in the full order **B** matrix representing four engines. The open-loop configuration then becomes **P=Pa/c*Pe**, where **Pe** is the quadruple form of the engine transfer function, $G^{z(\text{lbs})}_{\delta_{\pi}(\%)}$. The quadruples for four different configurations were obtained as described in Reference 9.

The flight conditions for each of the configurations are summarized in the table below.

Configuration Summary - Gear Up

| Config. Number | Weight (lbs) | Altitude (Ft MSL) | Airspeed (Knots) | Flaps (%) | CG % MAC |
|---|---|---|---|---|---|
| 1 | 140,000 | 4,000 | 160 | 0 | 20.85 |
| 2 | 140,000 | 4,000 | 145 | 30 | 20.85 |
| 3 | 160,000 | 4,000 | 175 | 0 | 20.85 |
| 4 | 140,000 | 4,000 | 155 | 30 | 20.85 |

The transfer functions were obtained from the quadruples using System Technology's CC Program[7]. These aircraft transfer functions are listed here with each respective row of numbers designating the corresponding configuration transfer function values. The nominal configuration, number 1, is represented by values in each row 1 below.

$$N^{\theta(\text{deg/sec})}_{z(\text{lbs})} = N^{\theta(\text{deg/sec})}_{z(\text{lbs})} / \Delta_{\text{long}}$$

$$N^{\gamma(\text{deg})}_{z(\text{lbs})} = N^{\gamma(\text{deg})}_{z(\text{lbs})} / \Delta_{\text{long}}$$

$N^{\theta(\text{deg/sec})}_{z(\text{lbs})} =$

| | | | | |
|---|---|---|---|---|
| 3.07E-04 | (0) | (-1.17E-05) | (0.40) (.61) | Conf #1 |
| 3.02E-04 | (0) | (1.36E-06) | (0.797, 0.568) | Conf #2 |
| 2.57E-04 | (0) | (0.292) | (0.644) | Conf #3 |
| 2.59E-04 | (0) | (2.68E-06) | (0.819, 0.508) | Conf #4 |

$N^{\gamma(\text{deg})}_{z(\text{lbs})} =$

| | | | | |
|---|---|---|---|---|
| 3.63E-05 | (0) | (0.203) | (0.370, 3.008) | Conf #1 |
| 2.36E-05 | (0) | (0.303) | (0.476,3.51) | Conf #2 |
| 2.77E-05 | (0.167) | (0.351, 3.038) | | Conf #3 |
| 1.91E-05 | (0) | ( 1) | (0.460 , 3.426) | Conf #4 |

$\Delta_{\text{long}} =$

| | | | |
|---|---|---|---|
| (1.438E-05) | (3.918E-02,0.130) | (0.652,1.382) | Conf #1 |
| (1.101E-05) | (7.423E-02,0.147) | (0.596,1.375) | Conf #2 |
| (3.949E-02,0.118) | (0.649,1.301) | | Conf #3 |
| (1.878E-05) | (7.190E-02,0.138) | (0.588,1.279) | Conf #4 |