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MULTILOOP PILOTING ASPECTS OF LONGITUDINAL APPROACH PATH CONTROL

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MULTILOOP PILOTING ASPECTS OF LONGITUDINAL APPROACH PATH CONTROL*

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Abstract

The multiple-loop aspects of longitudinal approach path control are analyzed to show the piloting problems involved in airspeed and altitude, or climb-rate, regulation and trim. Theoretically desirable and undesirable features of overall control, which in detail depend on the stick and throttle piloting technique (loop structure) employed, are delineated in general terms. Certain of the more important piloting problems are illustrated by applying the theoretical considerations to pertinent examples of experimental flying qualities results.

I. Introduction

The title and subject of this paper may appear somewhat mundane relative to conventional aircraft which generally seem to impose no more than standard difficulties on the pilot during the approach and landing flight phase. However, even for such aircraft, especially when they are required to approach at speeds below that for minimum thrust, flight path control problems can arise which must be handled by the pilot or circumvented by the automatic throttle system designer. Also, otherwise "conventional" aircraft are sometimes fitted with direct lift or drag devices, and proper integration of such devices into the flight control system, or selective use by the pilot, is not clearcut; nor is the question of when such devices are necessary, fully resolved.

When we turn to powered STOL and VTOL aircraft, the problems and concerns increase. Now the approach speed will, almost inevitably, be below the minimum thrust speed. Also, there will be a rich variety of available controls akin to those for a "conventional" aircraft with direct lift and drag, only more so. That is, lift and drag changes may, for example, be accomplished by either, or combinations of, change in power, thrust-line tilt, nozzle deflection, flap setting, boundary layer control bleed, or angle of attack. It is quite often very difficult to decide which control combination to use, or when to switch to an alternative set, not only at the design stage but sometimes when actually flying the aircraft. Similar questions relative to the design of the flight control system are additionally complicated by considerations of necessary vs. desirable complexity and reliability, and conflicting initial investment and maintenance/ availability costs.

The purpose of this paper is to outline and illustrate an analytic attack directed at better fundamental understanding of the problems and concerns noted above and possible solutions thereto.† In order to reduce the analytic considerations to their bare essentials, the assumption is made that only two controls are involved, stick and throttle. In essence, it is considered that either of these controls may, for a given aircraft, be whatever appropriate combination of real controls produces the assumed control effectiveness values in terms of the resulting X and Z forces and pitching moments, M. It is a simple matter, once desirable vs. undesirable "stick" and "throttle" control qualities are delineated, to determine the corresponding real control combinations for a particular aircraft.

The generic analytic considerations given in the next section (II) are directed toward identifying transfer function forms and factors indicative of control difficulties. To show the basic origins of the factors (poles and zeros) certain simplifying assumptions are made. Whether or not these assumptions hold does not detract from the general usefulness of the resulting conclusions which are given in terms of the factors themselves, their closed-loop equivalents, or the resulting closed- or open-loop transfer function and time-response properties.

These analytic considerations and resulting conclusions are given a certain amount of substance by reference to pertinent applicable literature. More substance is supplied by the specific examples presented in Section III, which were selected to illustrate certain more important problems and the general applicability of the "rules" for "good" or "bad" flying qualities given in Section II.

Both the generic and the specific closed-loop analyses are based on methods and pilot models which have been utilized in similar connections for the past ten years. These methods and models are presented with only rudimentary explanations in deference to exposing more interesting and newer developments; however, liberal reference is made to the basic underlying literature.

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†While problems associated with flight director functional design (i.e., suitable mixing, equalization and display of pertinent signals) are not specifically treated, the basic analytic considerations exposed here have proven extremely effective in this regard (e.g., Refs. 1 and 2).

II. Generic Longitudinal Path Control Considerations

As indicated above we will, for complete generality, consider the classical two-control problem — use of stick and throttle to control airspeed (u) and altitude (h) or rate of climb ($\dot{h}$) on a landing approach path. The block diagrams of Fig. 1 show two alternative control structures where the specific suitability of either depends upon the intimate details of the aircraft characteristics.

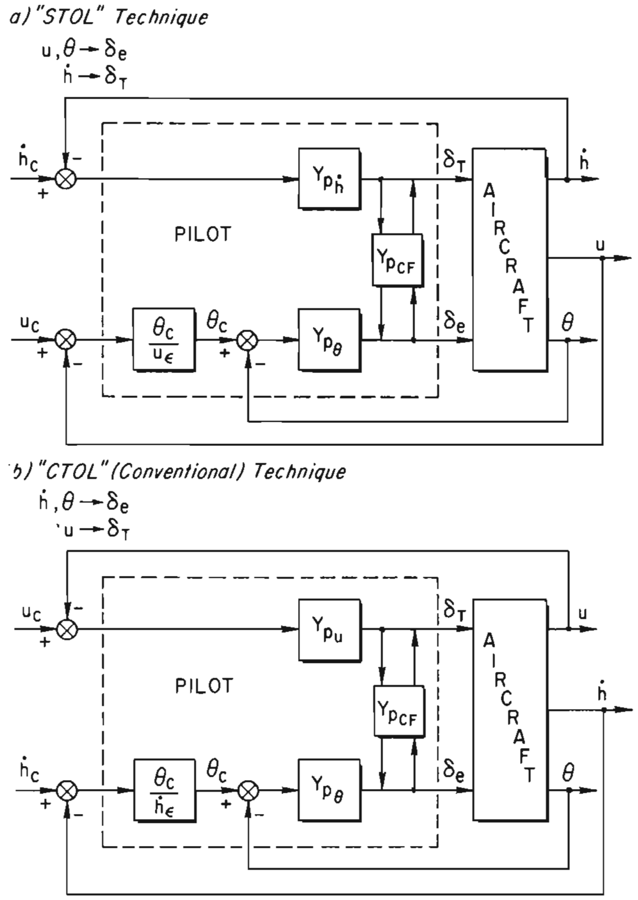


Figure 1. Two Representative Piloting Techniques

Notice that for both alternatives the innermost loop involves control of pitch attitude (θ) with the stick, or elevator (δ_e). This fundamental control is necessary to provide damping (e.g., of the phugoid motions) and other desirable equalization (i.e., faster closed-loop response) of the outer-loop motions. It is also, of course, necessary to control and regulate angle of attack (α), especially in gusty air, and thereby to preserve the stall margin.

The block diagrams are shown with all feedback and feedforward, or crossfeed, elements intact. However, these most general structures are only indicative of the possibilities. As noted above, the use of these possible modes of control depends on the specific aircraft response characteristics involved, and on the nature of the specific piloting task. For example, if the pilot's specific task, at the moment, is to correct an off-nominal airspeed and altitude (or sink rate) condition, the initial portions of such a re-trimming maneuver may well be accomplished open loop, with or without crossfeed. However, as the aircraft nears its nominal condition on target speed and glide slope, the pilot closes the necessary loops to achieve good regulation on the desired path. Thus, we distinguish between regulatory, closed-loop control about a desired operating point and "open"-loop control (with final regulation) to achieve a change in the operating point.

Another distinction resides in the relative priorities assigned to the closed-loop control activities, and generally these follow the speed-of-response properties of the attendant motions. Thus, attitude control which is fast response is usually of highest priority; indeed, as already mentioned, it is generally necessary and implicit regardless of alternative speed and height control activities. The next fastest response is usually in altitude or climb rate; therefore, it receives higher priority than airspeed control which is usually sluggish and slow by comparison. Accordingly, the primary path control input is that used to regulate altitude or its rate, and the secondary input is used to control or to trim airspeed. Thus, referring to the alternative loop structures shown in Fig. 1, the throttle (δ_T) is the primary path control for the "STOL" mode of operation, with secondary attitude (through elevator or stick) inputs to keep airspeed within tolerance. Conversely, for the "CTOL" mode of operation, attitude control of h or $\dot{h}$ is primary, and throttle control of u is secondary.

The foregoing hierarchy of control breaks down, of course, when the pilot's task is to change the operating point. Then the primary consideration is whether the change necessitates an increase or decrease in energy or simply an energy exchange. For instance, in an abort maneuver, the primary input is obviously thrust or throttle to increase the available energy. Similarly, for low and slow (or high and fast) conditions, relative to those desired, where total potential and kinetic energy are low (or high), thrust is the primary input. Conversely, for high and slow, or low and fast, where an energy interchange is indicated, attitude is the primary input, and throttle is used to obtain final trim.

The notion of primary and secondary path control inputs serves not only to order the loop-closing sequence but also to provide guidance in selection of the most probable crossfeeds.# Assuming that the pilot finds "coordinating" crossfeeds helpful to "purify" responses, it seems unlikely that he would crossfeed a primary control from a secondary input. Such crossfeeds would superpose lower frequency (primary) inputs on the basic "high" frequency primary control activity; in this respect, these crossfeeds would appear to be, at best, ineffective and, at worst, confusing. On the other hand,

#Available pilot describing functions, derived from data obtained in two-control multiple-loop situations, are usually based on pure feedback structures.[3, 4] However, the data and conclusions of Ref. 5 indicate, but do not specifically quantify, the pilot's selective use of crossfeed.

crossfeeding secondary control motions in response to primary inputs provides quicker, effective trimming of the secondary response. However, since trimming is basically a low frequency process, such higher frequency crossfeeding in direct response to primary inputs is considered unlikely except on an intermittent basis, e.g., for primary inputs above some threshold level. Based on this reasoning we hypothesize that crossfeed, if used, will be from primary to secondary control, and will only be active above some threshold level of primary input. The net effect of this hypothesized behavior on regulatory closed-loop activities is to place them somewhere between pure feedback and feedback plus pertinent crossfeeds.

Regulatory Closed-Loop Control

On the basis of the above discussion, the pertinent closed-loop transfer functions can now be written and the generic effects of aircraft characteristics thereon delineated. For generality, the presence and use of a primary-to-secondary control crossfeed is assumed, and the conditions under which such an assumption appears valid are later discussed. Proceeding then from inner to outer loops, neglecting control-system and engine-response dynamics, utilizing standard multiple-loop notation and formulations,(6, 7, 8) and denoting the various pilot transfer functions (more properly, quasilinear describing functions) by $Y_{P_i}(s)$[†] where the i subscript is specialized to indicate the particular loop involved:

Elevator (stick) inputs used to command θ:

$$\frac{\theta}{\theta_c} = \frac{Y_{P_\theta}N^{\theta}_{\delta_e}}{\Delta + Y_{P_\theta}N^{\theta}_{\delta_e} = \Delta'} \qquad (1)$$

$$\frac{\dot h}{\theta_c} = \frac{N^{\dot h}_{\delta_e}}{N^{\theta}_{\delta_e}}\left(\frac{\theta}{\theta_c}\right) = \frac{Y_{P_\theta}N^{\dot h}_{\delta_e}}{\Delta'} \qquad (2)$$

$$\frac{u}{\theta_c} = \frac{N^{u}_{\delta_e}}{N^{\theta}_{\delta_e}}\left(\frac{\theta}{\theta_c}\right) = \frac{Y_{P_\theta}N^{u}_{\delta_e}}{\Delta'} \qquad (3)$$

Throttle inputs in the presence of θ inner loop:

$$\frac{\theta}{\delta_T} = \frac{N^{\theta}_{\delta_T} + Y_{P_\theta}N^{\theta\,\theta}_{\delta_T\delta_e}}{\Delta'} = \frac{N^{\theta}_{\delta_T}}{\Delta'} \qquad (4)$$

$$\left.\frac{\dot h}{\delta_T}\right]_{\theta\to\delta_e} = \frac{N^{\dot h}_{\delta_T} + Y_{P_\theta}N^{\dot h\,\theta}_{\delta_T\delta_e}}{\Delta'} \qquad (5)$$

$$\left.\frac{u}{\delta_T}\right]_{\theta\to\delta_e} = \frac{N^{u}_{\delta_T} + Y_{P_\theta}N^{u\,\theta}_{\delta_T\delta_e}}{\Delta'} \qquad (6)$$

"Zero error" crossfeeds to purify primary $\dot h$ response (i.e., to hold u = 0):

$$u = \left(\frac{u}{\delta_T}\right)\delta_T + \left(\frac{u}{\theta_c}\right)\theta_c = 0 \;;$$

$$\theta_{CF}{}^{§} \equiv \frac{\theta_c}{\delta_T} \equiv \frac{1}{T_{CF}} \qquad (7)$$

$$\theta_{CF_o} = -\frac{u/\delta_T}{u/\theta_c} = -\frac{N^{u}_{\delta_T} + Y_{P_\theta}N^{u\,\theta}_{\delta_T\delta_e}}{Y_{P_\theta}N^{u}_{\delta_e}}$$

"STOL" control mode, with crossfeed:

$$\left.\frac{\dot h}{\delta_T}\right]_{\substack{\theta\to\delta_e\\ \Delta\theta=\theta_{CF}\delta_T}} = \left.\frac{\dot h}{\delta_T}\right]_{\theta\to\delta_e} + \left(\frac{\dot h}{\theta_c}\right)\theta_{CF} = \frac{N^{\dot h}_{\delta_T} + Y_{P_\theta}\left(N^{\dot h\,\theta}_{\delta_T\delta_e} + \theta_{CF}N^{\dot h}_{\delta_e}\right)}{\Delta'} \qquad (8)$$

$$\left.\frac{\dot h}{\delta_T}\right]_{\substack{\theta\to\delta_e\\ \Delta\theta=\theta_{CF}\delta_T\\ u\to\delta_e}} = \frac{N^{\dot h}_{\delta_T} + Y_{P_\theta}\left(N^{\dot h\,\theta}_{\delta_T\delta_e} + \theta_{CF}N^{\dot h}_{\delta_e}\right) + Y_{P_u}N^{\dot h\,u}_{\delta_T\delta_e}}{\Delta' + Y_{P_u}N^{u}_{\delta_e}} \qquad (9)$$

$$\left.\frac{u}{\theta_c}\right]_{\substack{\theta\to\delta_e\\ \Delta\theta=\theta_{CF}\delta_T\\ \dot h\to\delta_T}} = \frac{Y_{P_\theta}\left\{N^{u}_{\delta_e} + Y_{P_h}\left.N^{u\,\dot h}_{\delta_e\delta_T}\right]_{\theta_{CF}}\right\}}{\Delta' + Y_{P_h}\left[N^{\dot h}_{\delta_T} + Y_{P_\theta}\left(N^{\dot h\,\theta}_{\delta_T\delta_e} + \theta_{CF}N^{\dot h}_{\delta_e}\right)\right]} \qquad (10)$$

"CTOL" control mode with crossfeed:

$$\left.\frac{\dot h}{\theta_c}\right]_{\substack{\theta\to\delta_e\\ \Delta\delta_T=T_{CF}\theta_c}} = \frac{\dot h}{\theta_c} + T_{CF}\left.\frac{\dot h}{\delta_T}\right]_{\theta\to\delta_e}$$

$$= \frac{Y_{P_\theta}N^{\dot h}_{\delta_e} + T_{CF}\left(N^{\dot h}_{\delta_T} + Y_{P_\theta}N^{\dot h\,\theta}_{\delta_T\delta_e}\right)}{\Delta'} \qquad (11)$$

$$= \frac{Y_{P_\theta}\left(N^{\dot h}_{\delta_e} + T_{CF}N^{\dot h\,\theta}_{\delta_T\delta_e}\right) + T_{CF}N^{\dot h}_{\delta_T}}{\Delta'}$$

[†]Section III discusses the usual simple form of Y_p and provides a background reference. .

[§]The crossfeed details are not specified exactly. The net result of the assumed θ_{CF} is that $\delta_e/\delta_T = Y_{P_\theta}\theta_{CF}$.

$$\left.\frac{u}{\delta_T}\right]_{\substack{\theta \to \delta_e \\ \dot{h} \to \delta_e \\ \Delta\delta_T = T_{CF}\theta_c}} = \frac{N^u_{\delta_T} + Y_{P_\theta} N^{u\,\theta}_{\delta_T\delta_e}\Big]_{T_{CF}} + Y_{P_h} N^{u\,\dot{h}}_{\delta_T\delta_e}\Big]_{T_{CF}}}{\Delta + Y_{P_\theta} N^{\theta}_{\delta_e}\Big]_{T_{CF}} + Y_{P_h} N^{\dot{h}}_{\delta_e}\Big]_{T_{CF}}} \tag{12}$$

$$= \frac{N^u_{\delta_T} + Y_{P_\theta} N^{u\,\theta}_{\delta_T\delta_e}\Big]_{T_{CF}} + Y_{P_h} N^{u\,\dot{h}}_{\delta_T\delta_e}\Big]_{T_{CF}}}{\Delta' + T_{CF} N^{\theta}_{\delta_T} + Y_{P_h}\left(N^{\dot{h}}_{\delta_e} + \frac{T_{CF}}{Y_{P_\theta}} N^{\dot{h}}_{\delta_T}\right)}$$

The appropriate basic aircraft numerators and the characteristic denominator are of the general forms shown in Table 1, which also displays approximations for the path-dominating poles and zeros in literal form. These approximations, based on the simplifying assumptions:

$$\gamma_o{}^{**} = X_{\delta_e} = Z_{\delta_e} = M_{\delta_T} = M_u = 0$$

are useful in establishing relative pole, zero locations and signs in terms of the remaining more basic aircraft derivatives.

<u>Dominant Factors Governing Loop Structure Selection</u>. To more clearly demonstrate path control problems and the dominant effects that influence the choice of control structure, it is convenient to consider situations where the θ loop can easily be, and is in fact, closed quite tightly. Because the resulting Y_{P_θ} characteristics are then of relatively large magnitude, $\theta/\theta_c \doteq 1$ over the frequency band of interest and the $\dot{h}$ and u transfer functions of Eqs. 2, 3, 5, and 6 are simplified to the ratios of ordinary and coupling numerators (e.g., $\dot{h}/\delta_T$ for large $Y_{P_\theta} \to N^{\dot{h}\,\theta}_{\delta_T\delta_e}/N^{\theta}_{\delta_e}$). In effect, the pertinent equations of motion then become those for constrained attitude,(9) and the <u>path</u> control transfer functions are given rather compactly (invoking the above simplifying assumptions) by the following forms and factors:

Characteristic:

$$\Delta' = N^{\theta}_{\delta_e} = M_{\delta_e}[s^2 + (-Z_w - X_u)s + (Z_w X_u - X_w Z_u)]$$

$$= M_{\delta_e}[s^2 + 2\zeta_\theta\omega_\theta s + \omega_\theta{}^2] \quad , \quad \text{or}$$

$$M_{\delta_e}(s + 1/T_{\theta_1})(s + 1/T_{\theta_2})$$

The latter form results if X_w is small or in general if $|X_w Z_u| << |Z_w X_u|$, then: (13)

$$\Delta' \doteq M_{\delta_e}(s - X_u)(s - Z_w)$$

with $1/T_{\theta_1} \doteq -X_u$ and $1/T_{\theta_2} \doteq -Z_w$.

Elevator Responses:

$$\frac{u}{\delta_e} = \frac{-M_{\delta_e}}{\Delta'}(X_\alpha - g)\left(s + \frac{gZ_w}{X_\alpha - g}\right) \tag{14}$$

$$= \frac{-M_{\delta_e}}{\Delta'}(X_\alpha - g)\left(s + \frac{1}{T_{u_1}}\right)$$

$$\frac{\dot{h}}{\delta_e} = \frac{M_{\delta_e}Z_\alpha}{\Delta'}\left[s - X_u + \frac{Z_u}{Z_w}\left(X_w - \frac{g}{U_o}\right)\right] \tag{15}$$

$$= \frac{M_{\delta_e}Z_\alpha}{\Delta'}\left(s + \frac{1}{T_{h_1}}\right)$$

Throttle Responses:

$$\frac{u}{\delta_T} = \frac{M_{\delta_e}X_{\delta_T}}{\Delta'}\left[s - Z_w + X_w\left(\frac{Z_{\delta_T}}{X_{\delta_T}}\right)\right] \tag{16}$$

$$= \frac{M_{\delta_e}X_{\delta_T}}{\Delta'}\left(s + \frac{1}{T_{u_\theta}}\right)^{\dagger\dagger}$$

$$\frac{\dot{h}}{\delta_T} = -\frac{M_{\delta_e}Z_{\delta_T}}{\Delta'}\left[s - X_u + Z_u\left(\frac{X_{\delta_T}}{Z_{\delta_T}}\right)\right] \tag{17}$$

$$= -\frac{M_{\delta_e}M_{\delta_T}}{\Delta'}\left(s + \frac{1}{T_{h_\theta}}\right)^{\dagger\dagger}$$

For conditions on the "frontside" of the thrust-required vs. speed curve, and $X_w << g/U_o$, the value of:

$$\frac{1}{T_{h_1}} \doteq \frac{1}{T_{\theta_1}} + \frac{Z_u}{Z_w}\left(X_w - \frac{g}{U_o}\right) \doteq \frac{1}{T_{\theta_1}} - \frac{Z_u}{Z_w}\frac{g}{U_o} \tag{18}$$

(see Eqs. 13 and 15) is positive, and somewhat less than $1/T_{\theta_1}$ (because gZ_u/U_oZ_w is always positive); at the same time, $1/T_{u_1} \doteq -Z_w \doteq 1/T_{\theta_2}$. Accordingly, the $1/T_{h_1}$ zero approximately cancels the $1/T_{\theta_1}$ pole, and the $1/T_{u_1}$ zero approximately cancels the $1/T_{\theta_2}$ pole. Then, $\dot{h}/\delta_e \doteq Z_\alpha/(s + 1/T_{\theta_2})$ and $u/\delta_e \doteq g/(s + 1/T_{\theta_1})$, so that the $\dot{h}$ and u responses are well separated and the $\dot{h}$ response is faster, in keeping with the usual control hierarchy. Under such conditions of favorable pole-zero cancellation, the natural control structure is the CTOL mode with primary control of $\dot{h}$ with elevator (or θ_c) and secondary control of u, as occasionally required (because of sluggish response), with throttle.

**The $\gamma_o = 0$ initial condition does not detract from the general applicability of these small perturbation relations. Basically, the $\dot{h}$ responses so computed are equivalent to deviations normal to the flight path stability axis for the usually small values of γ_o pertinent to approach conditions.

††As noted above, the u and $\dot{h}$ throttle-response numerators are the coupling numerators which apply when two (or more) control inputs are involved; hence the modified notation which reflects conventional multiloop practice.(6-8)

TABLE 1

TRANSFER FUNCTION FORMS AND LITERAL APPROXIMATE FACTORS

FACTORED FORMS	APPROXIMATE FACTORS*
$\Delta(s) = \underbrace{(s^2 + 2\zeta_p\omega_p s + \omega_p^2)}(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)$ or $\left(s + \frac{1}{T_{p_1}}\right)\left(s + \frac{1}{T_{p_2}}\right)$	$\omega_{sp}^2 \doteq M_qZ_w - M_\alpha$ $2\zeta_{sp}\omega_{sp} \doteq -(Z_w + M_q + M_{\dot\alpha})$ ω_p^2 or $\frac{1}{T_{p_1}T_{p_2}} \doteq \frac{gM_wZ_u}{Z_wM_q - M_\alpha}$ $2\zeta_p\omega_p$ or $\left(\frac{1}{T_{p_1}} + \frac{1}{T_{p_2}}\right) \doteq -X_u$
$N_{\delta_e}^{\theta}(s) = A_\theta\left(s + \frac{1}{T_{\theta_1}}\right)\left(s + \frac{1}{T_{\theta_2}}\right)$ $\left[s^2 + 2\zeta_\theta\omega_\theta s + \omega_\theta^2\right]$	$A_\theta \doteq M_{\delta_e}$ $\frac{1}{T_{\theta_1}}\frac{1}{T_{\theta_2}} = \omega_\theta^2 = Z_wX_u - X_wZ_u$ $\frac{1}{T_{\theta_1}} + \frac{1}{T_{\theta_2}} = 2\zeta_\theta\omega_\theta = -X_u - Z_w$
$N_{\delta_e}^{u} = A_u\left(s + \frac{1}{T_{u_1}}\right)\left(s + \frac{1}{T_{u_2}}\right)$	$\frac{A_u}{T_{u_2}} \doteq M_{\delta_e}(X_\alpha - g)$ $\frac{1}{T_{u_1}} \doteq \frac{gZ_w}{X_\alpha - g}$
$sN_{\delta_e}^{h} = A_h\left(s + \frac{1}{T_{h_1}}\right)\left(s + \frac{1}{T_{h_2}}\right)\left(s + \frac{1}{T_{h_3}}\right)$	$\frac{A_h}{T_{h_2}T_{h_3}} \doteq -M_{\delta_e}Z_\alpha$ $\frac{1}{T_{h_1}} \doteq -X_u + \frac{Z_u}{Z_\alpha}(X_\alpha - g)$
$N_{\delta_T}^{\theta} = A_{\theta_T}\left(s + \frac{1}{T_{\theta_{T_1}}}\right)\left(s + \frac{1}{T_{\theta_{T_2}}}\right)$	$\frac{A_{\theta_T}}{T_{\theta_{T_2}}} \doteq Z_{\delta_T}M_w$ $\frac{1}{T_{\theta_{T_1}}} \doteq -X_u + Z_u\frac{X_{\delta_T}}{Z_{\delta_T}}$
$N_{\delta_T}^{u} = A_{u_T}\left(s + \frac{1}{T_{u_T}}\right)\left(s^2 + 2\zeta_{u_T}\omega_{u_T}s + \omega_{u_T}^2\right)$	$A_{u_T}\omega_{u_T}^2 \doteq -X_{\delta_T}M_\alpha$ $\frac{1}{T_{u_T}} \doteq \frac{g}{U_o}\frac{Z_{\delta_T}}{X_{\delta_T}}$
$sN_{\delta_T}^{h} = A_{h_T}\left(s + \frac{1}{T_{h_T}}\right)\left(s^2 + 2\zeta_{h_T}\omega_{h_T}s + \omega_{h_T}^2\right)$	$A_{h_T}\omega_{h_T}^2 \doteq Z_{\delta_T}M_\alpha$ $\frac{1}{T_{h_T}} \doteq Z_u\frac{X_{\delta_T}}{Z_{\delta_T}}$
$sN_{\delta_e\delta_T}^{\theta\ h} = A_{h_\theta}\left(s + \frac{1}{T_{h_\theta}}\right)$	$A_{h_\theta} \doteq -Z_{\delta_T}M_{\delta_e}$ $\frac{1}{T_{h_\theta}} \doteq -X_u + Z_u\frac{X_{\delta_T}}{Z_{\delta_T}}$
$sN_{\delta_e\delta_T}^{h\ u} = -sN_{\delta_T\delta_e}^{h\ u} = A_{h_u}\left(s + \frac{1}{T_{h_{u_1}}}\right)\left(s + \frac{1}{T_{h_{u_2}}}\right)$	$\frac{A_{h_u}}{T_{h_{u_1}}T_{h_{u_2}}} \doteq -X_{\delta_T}M_{\delta_e}Z_\alpha + Z_{\delta_T}M_{\delta_e}(X_\alpha - g)$
$N_{\delta_e\delta_T}^{\theta\ u} = A_{u_\theta}\left(s + \frac{1}{T_{u_\theta}}\right)$	$A_{u_\theta} \doteq X_{\delta_T}M_{\delta_e}$ $\frac{1}{T_{u_\theta}} \doteq -Z_w + X_w\frac{Z_{\delta_T}}{X_{\delta_T}}$

*For $\gamma_o = X_{\delta_e} = Z_{\delta_e} = M_{\delta_T} = M_u = 0$.

Notice too that the initial $\dot{h}/u$ response ratio is given by Z_α/g, a handling qualities parameter most often used to characterize short-period response (e.g., see Ref. 10).

It would appear from the above that making $1/T_{h_1}$ exactly equal to $1/T_{\theta_1}$ would be ideal from the standpoint of pole-zero cancellation and frequency separation. However, if this were attempted by making $X_w = g/U_o$ (e.g., through an angle-of-attack autothrottle) on the basis of Eq. 18, the effects would not be wholly beneficial. For one thing, the values of $1/T_{\theta_1}$ and $1/T_{\theta_2}$ would approach each other ($1/T_{\theta_1}$ increasing and $1/T_{\theta_2}$ decreasing) and might couple to produce an ω_θ oscillation (Eq. 13 for large X_w); also, the u/δ_e transfer function numerator (Eq. 14) would be a pure gain, $-gZ_w$. Therefore, the $\dot{h}/\delta_e$ response would not necessarily be ideal, because of inexact $1/T_{h_1}$, $1/T_{\theta_1}$ cancellation; and the u/δ_e response would consist of both the $1/T_{\theta_1}$ and $1/T_{\theta_2}$ aperiodic modes (or be oscillatory if coupled). Under these circumstances, despite the "favorably" positive value of $1/T_{h_1}$, the CTOL mode of control would appear to be quite poor. If the STOL mode provided more favorable cancellation, it might be better. However, if coupling were present in the form of a second-order, ω_θ, mode, neither piloting structure would provide cancellation, since all the numerators (Eqs. 14-17) are first-order. Then, the choice of structure would logically depend on possible differences in the magnitude (and time history) of the secondary to primary response ratio, $u/\dot{h}$.

The most obvious, and classical, reason for considering a switch from the CTOL to the STOL mode loop structure is a negative value of $1/T_{h_1}$ which occurs on the "backside" of the thrust-required vs. speed curve. For such situations, closing the $\dot{h}/\delta_e$ transfer function (Eq. 15), i.e., holding altitude with elevator, results in an aperiodic (speed) divergence characterized by the negative value of T_{h_1}. However, while the STOL mode will normally avoid such difficulties and is the usually preferred "backside" technique (discussed more fully in Section III), it may under certain conditions present difficulties warranting a closer examination of the CTOL mode of control.

Suppose, for instance, that $1/T_{h_\theta}$ (Eq. 17) approaches $1/T_{\theta_2}$ due to positive thrust inclination (i.e., $X_{\delta_T}/Z_{\delta_T} < 0$) so that $Z_u(X_{\delta_T}/Z_{\delta_T}) \doteq -Z_w$. Then, the $\dot{h}/\delta_T$ transfer function reduces to $-Z_{\delta_T}/(s + 1/T_{\theta_1})$, which for normal values of $1/T_{\theta_1} \doteq -X_u$ has a relatively slow response. At the same time, the negative value of $X_{\delta_T}/Z_{\delta_T}$ would tend to reduce $1/T_{u_\theta}$ for normally positive X_w (Eq. 16), bringing it closer to $1/T_{\theta_1} \doteq -X_u$. The resulting u/δ_T transfer function would then approach $X_{\delta_T}/(s + 1/T_{\theta_2})$, which represents a relatively fast response. Accordingly, not only would $\dot{h}$ control with δ_T be poor because of sluggish response, but the usual primary and secondary response roles would be reversed, i.e., u would respond faster than $\dot{h}$. However, the steady-state response ratio, $u/\dot{h}$, given by $-X_{\delta_T}T_{\theta_2}/Z_{\delta_T}T_{\theta_1} \doteq -X_{\delta_T}X_u/Z_{\delta_T}Z_w$ could conceivably be so small that the u perturbations might not be too troublesome.

The conclusion following from the above discussion is that there is no simple rule which can guarantee the selection of the correct piloting structure. Backsidedness is a primary clue but it must be tempered with dynamic coupling, frequency separation/ordering, and response ratio considerations.

Crossfeed Considerations. The conditions surrounding the selection of the appropriate closed-loop structure require further extension for possible crossfeeds. Still considering situations where the attitude loop is tightly closed, the zero-error crossfeed is given by (Eq. 7):

$$\theta_{CF_o}(s) = \frac{1}{T_{CF_o}(s)} = -\frac{N^{u\ \theta}_{\delta_T \delta_e}}{N^u_{\delta_e}} \doteq -\frac{X_{\delta_T}\left(s + \frac{1}{T_{u_\theta}}\right)}{\left(X_\alpha - g\right)\left(s + \frac{1}{T_{u_1}}\right)} \qquad (19)$$

where

$$\frac{1}{T_{u_\theta}} \doteq -Z_w + \frac{Z_{\delta_T}}{X_{\delta_T}} X_w$$

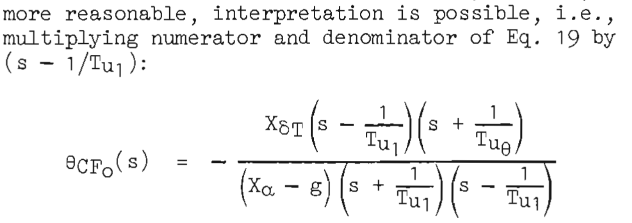
$$\frac{1}{T_{u_1}} \doteq \frac{gZ_w}{X_\alpha - g}$$

In general, either or both $1/T_{u_\theta}$ and $1/T_{u_1}$ can become negative for sufficiently high positive values of X_w (e.g., for an autothrottle utilizing α feedback) and the usually negative sign of $Z_{\delta_T}/X_{\delta_T}$ (for positive thrust inclination). When $1/T_{u_1}$ is negative, $\theta_{CF_o}(t)$, for a step δ_T input increases exponentially (diverges) with time; thus, there is no finite steady-state value. However, another, more reasonable, interpretation is possible, i.e., multiplying numerator and denominator of Eq. 19 by $(s - 1/T_{u_1})$:

$$\theta_{CF_o}(s) = -\frac{X_{\delta_T}\left(s - \frac{1}{T_{u_1}}\right)\left(s + \frac{1}{T_{u_\theta}}\right)}{\left(X_\alpha - g\right)\left(s + \frac{1}{T_{u_1}}\right)\left(s - \frac{1}{T_{u_1}}\right)}$$

$$\doteq \frac{X_{\delta_T}}{\left(X_\alpha - g\right)} \frac{\left(s + \frac{1}{T_{u_\theta}}\right)}{\left(s - \frac{1}{T_{u_1}}\right)} e^{-2T_{u_1}s} \qquad (20)$$

where the last step utilizes the first-order Pade approximation, $e^{-\tau s} \doteq [s - (2/\tau)][s + (2/\tau)]$, valid only when τ is small relative to the times of interest. For negative T_{u_1}, $\theta_{CF_o}(t)$, which is now basically convergent, must, however, start before the δ_T step input by $-2T_{u_1}$ sec. This required advancement in start time for the crossfed θ_{CF} is consistent with the effective delay in the u/θ_c response when $1/T_{u_1}$ is negative, as sketched below.



u Response to Step θ_c for Negative $1/T_{u_1}$

Here, consistent with the large positive values of X_w required to make $1/T_{u_1}$ negative, we have assumed that the characteristic, θ numerator, modes are coupled (Eq. 13), i.e., oscillatory with good damping. Notice that the u response is roughly zero for a time delay interval related to $-1/T_{u_1}$; hence, the crossfeed θ_c must start earlier to be effective.

Another aspect of the sketched u response is that, initially, u is essentially decoupled (from $\dot{h}$) for θ_c inputs. Also, although not shown, the value of $1/T_{h_1}$ is probably positive, reflecting the large positive value of X_w (see Eq. 15). It appears, therefore, that the use of throttle as the primary closed-loop control is unwarranted, on the basis of the decoupled u and stable $\dot{h}$ responses to θ_c; and that the assumed crossfeed and loop structure are probably both incorrect.

A general conclusion afforded by this example is that whenever the zero error crossfeed has a positive pole (negative factor), the assumed loop structure bears careful re-consideration.

A more usual concern is that even for positive values of T_{u_θ} and T_{u_1} the $\theta_{CF_0}(t)$ for a step throttle input may vary considerably with time. If this variation is too extreme it is difficult for the pilot to learn and "program" even for discrete maneuvers and doubly so for closed-loop control. Accordingly, we hypothesize that crossfeed will not be used (even intermittently) in closed-loop operations when the ideal crossfeed requires more than a 30 per cent change over the time interval from three to ten seconds (following the primary input). The 30 per cent value is arbitrary; it reflects the fact that zero per cent change (pure gain) is ideally desirable and that pilots are relatively insensitive (from a rating standpoint) to time-invariant gain changes of the order of 50 per cent.[11] The times selected are those consistent with the frequency band of interest for closed loop $\dot{h}$ and u control, respectively.[8, 12, 13] This general "rule" for judging the possible efficacy of an assumed crossfeed also handles situations where the values of $1/T_{u_\theta}$ or $1/T_{u_1}$ may be negative but quite small. For positive values it is more convenient and, because of its tentative nature, just as reasonable, to extend the time interval to infinity, i.e., to consider the ratio of the 3 sec and steady-state values.

Pilot-Centered Path Regulation Problem Areas. In order to judge the approach and landing path regulation suitability of a given configuration, it is advisable to catalog some of the more prominent sources of pilots' complaints and difficulties. However, before proceeding in this negative vein, it is appropriate to discuss those properties found desirable. For both discussion and catalog, the assumption, as in the foregoing, that the attitude loop is tightly closed and that such closure does not interfere with path control will not be made, i.e., attitude-loop-related problems will be considered.

Relative to good path regulation properties, the pilot would like:

- **Inner loop (e.g., attitude) control integrity and equalization potential.** The inner, attitude loop, because it is fundamental to path control regardless of piloting technique, should have response characteristics generally faster, better damped, etc., than the primary path loop. A minimum open-loop crossover frequency capability of the order of 2 rad/sec[14] with adequate gain and phase margins and without (or "low") pilot equalization is desirable. The open-loop "dc" gain should be high enough to prevent low frequency attitude "drifting." Closing the inner loop should provide favorable: improvement of the phugoid mode damping, to inhibit airspeed fluctuations; and overall path mode equalization, insensitive to and tolerant of the specific θ-loop gains used by the pilot (i.e., "tightness" or "looseness" of attitude control).

- **Adequacy and ordering of path control loop bandwidths.** Basically, the path-mode bandwidth requirements are predicated on good closed-loop performance capabilities and disturbance (i.e., gust and shear) suppression. The $\dot{h}$-loop (with θ closed) should have faster response than the u-loop by at least a factor of 3; its minimum open-loop crossover capability, with adequate gain and phase margins and without equalization, should be of the order of 0.5 rad/sec.[12]

- **Uncoupled or complementary control responses.** The $\dot{h}$ and u responses (with θ closed) to the controls should be separated so that they do not interfere. Thus, it should be possible to control $\dot{h}$ without exciting excessive excursion in u, and vice versa. However, if some degree of coupling exists, the responses should be complementary (i.e., the control actions required to regulate one path variable (e.g., $\dot{h}$) help in the regulation of the other (e.g., u).

- **Minimum depletion of safety margins.** During path regulation and control activities, stall, buffet, control, comfort, etc., boundaries must never be exceeded; and excursions into the available margins should be minimized.

- **Control economy.** Control "economy" refers to the pilot's desire to use as simple, and as easily maintained, a control strategy as possible, e.g., minimum number of nonsensitive feedback loops with little or no equalization and/or crossfeeds. Such "economical" control imposes minimal demands on the pilot's attention and thereby allows him sufficient excess capacity for other functions.

- **Control harmony.** The preceding good qualities have primarily been directed at the dynamic aspects of control, assuming that the pilot loop gains required to achieve control are "comfortable" and "harmonious." An otherwise good airplane (dynamically) can be seriously degraded if control sensitivities are too high or too low, and/or if the relative sensitivities are disproportionate.

Path regulation problem areas will arise in varying degree whenever there are deviations from the "good" properties listed above. However, such generalization is of little utility in pinpointing the specific sources of the pilot's complaint or in suggesting aircraft and/or flight control system modifications to improve pilot acceptance. To enhance appreciation for the particular kinds of problems encountered, the following catalog has been assembled based on past experience. Some of this experience will later be used to illustrate the detailed nature of specific problems. Undoubtedly, other kinds of problems exist to be discovered in the future.

Attitude Control

- **Inadequate bandwidth** problems are often associated with low short-period stiffness where the attitude response is dominated by the phugoid mode. These situations, as noted, e.g., in Refs. 14 and 15, require excessive pilot lead compensation (i.e., $T_{L_\theta} > 1$ sec) to attain the desired crossover frequency range. Increasing T_L is directly associated with degrading (increasing) handling quality ratings; to get a satisfactory, 3.5, rating, T_L must be less than approximately 1 sec.[16, 17]

- **Inner-outer loop equalization conflict** results when pilot lag, T_{I_θ}, is required in the attitude loop. Reference 14 illustrates how lag equalization in the θ-loop restricts the path mode (i.e., h) bandwidth. Typically, these situations exist where attitude is used to control altitude and the attitude numerator factor, $1/T_{\theta_2}$ (i.e., altitude lag), is much less than one.

- **Low static gain** properties are another manifestation of backsidedness; ie., from Eq. 18, for $1/T_{h_1} < 0$, $1/T_{\theta_1} < -Z_{u}g/U_oZ_w \doteq \omega_p^2 T_{\theta_2}$, and the static gain is then less than the short-period "gain."[18] Sufficiently low values of static gain limit the pilot's ability to provide separation of u and $\dot{h}$ responses. Also, attitude trimmability and the use of attitude as a speed reference are degraded, resulting in increased attentional demands on the pilot.[3, 19]

- **Over-sensitivity to gain/equalization** occurs when the inner attitude loop or resulting outer loop crossover frequencies or bandwidths are very sensitive to changes in pilot gain (K_{p_θ}) or lead (T_{L_θ}). References 6 and 19 illustrate, respectively, situations in which attitude gain and lead-equalization sensitivity were the underlying control problems affecting path regulation.

Path Control

- **Performance reversals** occur when increased attention and control activity, i.e., increased pilot gain and/or lead, cause a net <u>loss</u> in performance. Typically, such reversals are multiloop in nature, in that the closure of the innermost loop restricts the path mode bandwidth.[3, 6] Other reversal situations involve so-called "boxed-in" conditions.[19, 20] In these cases, the pilot is constrained not only to a given control strategy, but also to narrowly confined values of gain and/or lead; increasing <u>or</u> decreasing gain/equalization causes an undesirable performance degradation.

- **Inadequate bandwidth** is primarily an altitude loop (with attitude closed) problem. When the loop crossover frequency is less than about 0.3 to 0.4 rad/sec,[12] the pilot rating will be unsatisfactory (PR > 3.5). Excessive lead equalization, required to achieve desirable bandwidth, will also be unsatisfactory (see above).

- **Inadequate response separation** refers to undesirable "mixing" of u and $\dot{h}$ responses. As noted above, this can be due to "inherent" coupling when the θ/δ_e numerator is oscillatory, or to thrust inclination effects which produce inadequate pole-zero cancellations in the appropriate u and $\dot{h}$ transfer functions. If the response in u is faster than that in $\dot{h}$ the "mixing" is especially bad; in general, u responses faster than about half the $\dot{h}$ response (assuming the latter is adequate, as above) are undesirable. Of course, the magnitude (and sign) of $u/\dot{h}$ is also important. For instance, a particularly troubling aspect of "inherent" (ω_θ) coupling occurs when the <u>initial</u> $u/\dot{h}$ response to elevator (or θ_c) becomes positive (e.g., due to $X_\alpha > g$, Eqs. 14 and 15). Then, since the $u/\dot{h}$ response to thrust is also generally positive, closure of either loop (u or $\dot{h}$) conflicts with closure of the remaining loop ($\dot{h}$ or u). That is, for a positive $\dot{h}$ response u is (initially, at least) positive; and a secondary control input to reduce u also reduces the desired $\dot{h}$ response. Such conditions tend to limit the pilot's primary regulation activities to the use of a single control; u perturbations are ignored.[13]

- **Difficult or conflicting crossfeeds** have already been discussed relative to dynamic problems. Additional difficulties arise when the necessary or required control actions are too large, are unnatural (e.g., reversed sign), or when they limit regulation performance (e.g., by reducing effective gain or bandwidth). Regardless of whether or not crossfeeds are actually used by the pilot, inspection of the zero-error crossfeed characteristics (θ_{CF_o}, T_{CF_o}) can provide useful clues in terms of the overall activities (either feedback or crossfeed) required to "purify" responses.

- **Excessive depletion of safety margins** can be caused by any combination of the above noted deficiencies. In general, however, the CTOL mode (controlling $\dot{h}$ with elevator) involves larger α excursions than the STOL mode ($\dot{h}$ with throttle), whereas the latter obviously involves larger thrust excursions. Thus, depending on whether the airplane is closer to a limiting condition on power or stall may dictate the choice of control strategy from a <u>safety</u> standpoint, provided there is no obvious choice from the ease-of-control standpoint.

- **Low (high) effective path gains** are those situations where an otherwise good airplane/flight control system suffers because of overly sensitive, overly sluggish or "disharmonious" control effectiveness. Departures in either direction from desirable gain levels result in degraded ratings and poorer pilot acceptance. Analysis of the regulation control activity in terms of rms control deflections or forces can sometimes provide a clue to degrading gain levels.[11, 21]

Open-Loop Changes in Operating Point (Trim Management)

As indicated earlier, the pilot's tasks are not all concerned with closed-loop regulation about a given operating point. He must also readily be able to perform essentially open-loop maneuvers to new operating points, as in: flare and touchdown; correcting off-nominal path and speed, including glide slope acquisition; transitions from cruise to landing configurations; and compensating for steady and sheared winds. All these tasks can be characterized in general by the need to change either airspeed or altitude (or sink rate) or both by a prescribed amount or (for transition) in some easily programmed manner. Assuming that the pilot can comfortably close the attitude loop and that such closure does not "interfere" with path and speed control directs attention back to the attitude constrained transfer functions of Eqs. 2, 3, 5, and 6, and the pertinent Table 1 forms and approximations. However, we now consider discrete, rather than continuous, primary and secondary inputs and appropriate crossfeeds and confine our attention to corrections about a near-nominal approach path.

Energy Change. For a trim change requiring an energy increase or decrease, thrust or throttle (δ_T) is the primary input; however, secondary $\theta_c(\delta_e)$ inputs are generally required to rapidly approximate the desired increases or decreases in <u>both</u> speed and altitude (or climb rate). Final achievement of the desired target conditions involves closed-loop regulation, as noted earlier; but the initial maneuver and appropriate pilot strategy involves open-loop coordinated, or crossfed, control inputs. Because both altitude and speed changes are desired, the appropriate crossfeed is not exactly the zero-error form (θ_{CF_o}) previously given. However, scaling θ_{CF_o} up or down directly scales the resulting u response to a throttle input, i.e.:

$$\frac{u}{\delta_T} = \frac{N^u_{\delta_T} + N^u_{\theta_c} K \theta_{CF_o}}{\Delta'} = \frac{N^u_{\delta_T} - K N^u_{\theta_c}\left(\frac{N^u_{\delta_T}}{N^u_{\theta_c}}\right)}{\Delta'} = (1 - K)\frac{N^u_{\delta_T}}{\Delta'} \qquad (21)$$

Therefore, $K\theta_{CF_o}$ can be taken as <u>indicative</u> of the stick activity required to coordinate a primary throttle input; where K is a constant, appropriate to the airspeed change desired. Note that for the postulated conditions, i.e., thrust input to increase, or decrease, both speed and altitude simultaneously, $1 - K$ is always positive.

As already noted, if $\theta_{CF_o}(t)$ is not roughly constant, it represents a difficult crossfeed for the pilot. Whether or not the rules previously postulated for the permissible time variation of θ_{CF_o} in regulatory tasks also apply to trim change tasks is a moot point. It would seem that for discrete inputs the permissible variations with time could be somewhat larger than those for continuous closed-loop inputs. Nevertheless, it can still be stated that desirable values of $\theta_{CF_o}(t)$ for both tasks are those that remain nearly constant.

The sign and magnitude of θ_{CF_o} are also important. A negative sign, or a very small magnitude, indicates that positive thrust inputs (without crossfeed) tend, respectively, to decrease speed or to produce essentially zero speed change. Since the pilot's intention in applying thrust is to increase both speed and climb (otherwise he would change attitude to effect an energy interchange), positive and reasonably large values of θ_{CF_o} are desirable for trim management. The only surprising aspect of this conclusion is the rejection of $\theta_{CF_o} = 0$ as a desirable condition. Since $\theta_{CF_o} = 0$ represents a "purified" response, i.e., only $\dot{h}$, it would seem normally desirable, at least from a regulatory standpoint. However, the above considerations suggest that such a condition is somewhat more complex from the trim management standpoint than necessary, i.e., thrust <u>and</u> stick inputs are always required when an energy increase is indicated. For conditions with positive θ_{CF_o}, certain u and $\dot{h}$ energy increases could conceivably involve <u>only</u> thrust inputs. In this regard zero and negative values of θ_{CF_o} infer less economy of control (more workload) than do reasonably positive values. This theoretical consideration needs more specific checking; however, it seems to correlate with the available evidence, as later discussed.

The upper limit on the positive magnitude of θ_{CF_o} is that the resulting α excursions must not be so large that they represent serious depletion of available stall margins.

While θ_{CF_o} appears to have some trim management significance when θ is easily and tightly controlled, the effects of opening this inner loop should also be considered. For example, if there are noticeable thrust-induced pitching moments, both $\dot{h}$ and u responses will depend on the extent to which the attitude-loop closure suppresses such moments. As indicated earlier, the pilot would like some latitude in all loop closure gains; accordingly, large thrust pitching moments are always undesirable,[22] since they impose a requirement for tight attitude control. However, small pitching moments may have desirable crossfeed consequences in the present context. For instance, when $\theta_{CF_o} = 0$, e.g., for thrust inclination near 90 deg, negative (nose down) pitching moments, if not suppressed by the attitude closure, would produce a positive u response. Then, the zero-error crossfeed, now expressed in terms of stick (positive aft) to throttle, $(\delta_s/\delta_T)_{CF_o}$, would be positive and favorable, rather than zero and possibly questionable. Reference 22 contains some experimental evidence which tends to confirm these considerations, e.g., "some aft thrust line effect was found to improve speed control." Also, "smaller speed excursions and less longitudinal control activity are apparent in the aft offset configuration...."

> Generalizing on the above observations: both $(\delta_s/\delta_T)_{CF_o}$ and θ_{CF_o} should be approximately constant (within 30%, say) for times between about 3 and 10 seconds; and either or both should be greater than zero but not so large as to imply excessive α excursions.

Energy Exchange. Turning now to energy exchange conditions, the primary input, as already noted, is θ_c. For backside conditions an increase in attitude will eventually produce <u>both</u> u and $\dot{h}$ <u>decreases</u>.

There is no steady-state energy exchange; and this is the essence of the backside problem. Therefore, thrust is always required as a final adjustment to keep $\dot{h}$ and u of opposite sign. The problem is similar to that in regulatory control and little distinction can profitably be made between regulation and energy exchange trim management for backside conditions.

For frontside conditions the desirable energy exchange usually occurs quite predictably with attitude inputs producing monotonic changes of opposite sign in $\dot{h}$ and u. However, if the frontsidedness is due to a large positive value of X_w (as in some autothrottle-equipped U.S. Navy aircraft), the initial u response is then opposite ($1/T_{u_1} < 0$ ‡‡) to the final response, which is quite conventional. However, the final response in $\dot{h}$, although of opposite (conventional) sign to u is quite large. The problem now is that there may be inadequate energy exchange potential because θ_c produces primarily a change in h. If the pilot wants to decrease airspeed with θ_c, he also incurs a large increase in $\dot{h}$. If he uses thrust to reduce this $\dot{h}$ error he increases airspeed, thereby negating his initially desired airspeed reduction. Formalizing this observation:

$$\text{for } h = 0 \qquad \left(\frac{h}{\theta_c}\right)\theta_c + \left(\frac{h}{\delta_T}\right)\delta_T = 0$$

$$\delta_{T_{CF}} \equiv \frac{\delta_T}{\theta_c} = -\frac{(h/\theta_c)}{(h/\delta_T)}$$

$$u = \left(\frac{u}{\theta_c}\right)\theta_c + \left(\frac{u}{\delta_T}\right)\left(\frac{\delta_T}{\theta_c}\right)\theta_c$$

$$= \left[\left(\frac{u}{\theta_c}\right) - \left(\frac{u}{\delta_T}\right)\frac{(h/\theta_c)}{(h/\delta_T)}\right]\theta_c$$

$$= \left(\frac{u}{\theta_c}\right)\left[1 - \frac{(h/u)_{\theta_c}}{(h/u)_{\delta_T}}\right]\theta_c$$

Considering steady-state values and "normalizing" with respect to the non-crossfed case:

$$\frac{\left.\dfrac{u}{\theta_c}\right]_{\delta_{T_{CF}}}}{\dfrac{u}{\theta_c}} = 1 - \frac{Z_\alpha X_{\delta_T}}{Z_{\delta_T}(X_\alpha - g)}\,\frac{T_{u_1}T_{h_\theta}}{T_{u_\theta}T_{h_1}} \qquad (22)$$

If the value of this ratio is small, the θ and α excursions required to effect airspeed trim (without disproportionate $\dot{h}$ excursions) are larger than usual by the inverse of the ratio. A ratio of 1/2, for example, means that a normal value of $U_o\theta_c/u_\epsilon$, about 0.3 deg for a 1 per cent change in speed, increases to 0.6 deg. Since airspeed fluctuations and usual tolerances approach 10 per cent or so (e.g., 5 kt for a 60 kt nominal approach speed), the resulting α and θ excursions in this example could be as high as 6 deg, an obviously serious incursion into the stall margin.

> Thus, the acceptability of a given (Eq. 22) ratio appears to depend largely on the specifically available stall margin.

Implications for Handling Quality Parameters, Criteria, and Correlations

The large number of parameters involved (e.g., Table 1), the multiple-loop aspects to be considered (e.g., Eqs. 1-12), and the possible closed- and open-loop problems that can occur present a labyrinthian path to the discovery of universal open-loop airplane-only parameters or criteria which can be used successfully to describe all the effects involved (see also Ref. 23). It may be possible eventually to correlate specific problems and effects with selected airplane parameters, remembering that many of the parameters are connected through basic derivatives. However, the process of examining all potential parameters in the light of correlatable data presents, in view of the dimensions of the problem, an enormous experimental burden.

A more viable alternative, in the authors' opinion, is to apply available and proven open- and closed-loop analysis techniques and general criteria to the development of a design methodology which can be used to discover and rectify fundamental and interacting problem areas. Once confidence in its validity has been established, the method can undoubtedly be reduced to simple computational programs, thereby to streamline the design and specification process (e.g., Ref. 17). In the body of this section we have presented the major considerations and analysis techniques, some already "verified" experimentally, which would form the core of a complete method. In the section to follow we shall further illustrate how certain experimentally-encountered piloting difficulties can be explained by application of these considerations and techniques.

III. Example Analytic Studies of Path Control Problems

In the following we present example results of analyses directed at explaining and understanding various rating trends and problems associated with multiple-loop approach control experiments and flight observations. In order to do this most economically, the selected loop closures involved are shown with little or no explanation of the manner in which the parameters comprising the pilot's transfer function,

$$Y_P = K_P\frac{(T_Ls + 1)}{(T_Is + 1)}e^{-\tau s} \qquad (23)$$

were individually established for each example. In general, the parameters were set by applying the "adjustment rules" which are an integral part of the complete Pilot Model.[11] In certain instances, complete adherence to all the adjustment rules is unnecessary and was not used in the interests of a simpler but still revealing analysis. For example,

‡‡Since $1/T_{u_1}$ is a pole in $\theta_{CF_o}(s)$, Eq. 7, the configuration may prove undesirable from the standpoint of divergent $\theta_{CF_o}(t)$ characteristics.

control of the low-frequency path modes is little influenced by the elimination of the time delay (τ) term, because its phase contribution for the frequencies of concern (below 1 rad/sec) is quite small.

The cases of most interest and complexity are those on the "backside" of the thrust-required vs. speed curve; therefore, most of the examples considered have this feature. For more examples of closed-loop analyses pertinent to frontside conditions, the reader is referred to the existing literature.[12, 14, 18, 25]

Example 1. Carrier Aircraft Approach-Speed Selection

This first example is also taken from the literature[6, 18, 26, 27] and represents a pioneering effort to apply multiple-closed-loop analyses to the approach path regulation problem. The situation considered was stick and throttle control of approach path and speed on an optical beam; and the analyses were directed at examining those flight test conditions, on a variety of U.S. Navy airplanes, where the pilots reported an "inability to control altitude or arrest rate of sink." This inability could not, at the time, be ascribed to any of the then-current approach speed selection parameters.

The very complete analyses of Ref. 6 considered both the basic loop structures shown in Fig. 1; angle-of-attack feedbacks to throttle or stick were also considered and analyzed. After many specific and generic loop closure exercises which took account of thrust and angle-of-attack lags it was decided that the probable piloting technique employed was $h \rightarrow \delta_T$, θ, $u \rightarrow \delta_e$, corresponding to the so-called STOL mode. This conclusion was supported in part by contacts with Navy pilots and by official Navy "doctrine." In analyzing this control structure it was discovered that, for certain conditions well on the "backside," primary control of altitude was very sensitive to the assumed inner (θ) loop gain. In fact, as airspeed was progressively decreased, increasing the pilot's θ-loop gain became less effective in increasing the outer loop, altitude control, bandwidth; and eventually an increase in gain resulted in a decrease in bandwidth and in altitude control performance.

The speed at which this reversal occurs was postulated as corresponding to incipient "inability to control altitude...." For lower speeds the harder the pilot tries, by tightening attitude control (normally effective in improving altitude response), the more he degrades his altitude performance. The altitude bandwidth sensitivity to attitude gain was computed for seven Navy carrier aircraft for a range of approach speeds; and the speed at which reversal occured (bandwidth:gain sensitivity = 0) was shown to compare favorably with pilot-selected approach speeds for five of the seven aircraft. The remaining two had other limiting problems, e.g., poor lateral control, forward visibility, etc. Finally, a simplified form of a "reversal criterion," based on assumptions equivalent to those for the Table 1 approximate factors and on the phugoid equations of motion (i.e., neglecting M_q, $M_{\dot{\alpha}}$, $\ddot{\theta}$ terms) was derived (see also Ref. 18); i.e., reversal occurs when:

$$\frac{1}{T_{\theta_1}T_{\theta_2}}\left(\frac{1}{T_{h_T}} - 2\zeta_p\omega_p\right) + \omega_p^2\left(\frac{1}{T_{\theta_1}} + \frac{1}{T_{\theta_2}} - \frac{1}{T_{h_T}}\right) = 0 \qquad (24)$$

It was later noticed that the "reversed" conditions could be improved by reductions in the static margin. This thesis was tested in a fixed-base simulator experiment with favorable confirmation in the work reported in Ref. 26. In this reference it was also explicitly shown that, for characteristics representative of then-current Navy carrier aircraft, two-loop control of attitude with elevator and altitude with throttle (without $u \rightarrow \delta_e$) caused only small perturbations in airspeed. These were, in fact, considerably smaller than those accompanying the complete three-loop CTOL mode of operation, i.e., h, $\theta \rightarrow \delta_e$; $u \rightarrow \delta_T$. While the CTOL mode exhibits some potential superiority relative to altitude control (noted and discussed in Ref. 6), it suffers by comparison with the STOL mode on two counts: u dispersions are increased as noted above, and three loops, rather than two (as for acceptable STOL mode performance), must be closed. In the latter sense, the CTOL structure violates the pilot's desire for control economy.

Another effort relative to this subject is reported in Ref. 27. Here the primary purpose of the work was to define a landing approach flight test program for a specific aircraft and to predict the flight results. Reversal effects were studied in detail and it was shown that the simple criterion was affected only slightly by the addition of the short-period mode. Also studied were the effects of drag variation (through use of landing gear and dive brakes) and c.g. shifts. The analyses indicated a spread of about 18 kt in the reversal speeds for extreme conditions of drag and c.g. configuration. Unfortunately, the flight tests were (later) conducted without either drag or c.g. changes.[28] However, the selected "comfortable" speed for a beam-guided approach was found to be limited by "loss of ability to control the flight path angle," as predicted. Also, the flight-determined "comfortable" approach speed range, between 130 and 140 kt, was satisfying close to the calculated reversal speed (corrected for weight differences) of 132 kt.

Example 2. Backside STOL Control as Influenced by Thrust Inclination

This example considers the conditions experimentally investigated in Ref. 13. A feature of this experiment was the use of an automatic inner, rate-command, attitude hold loop which eliminated attitude control problems from the path control picture. Also, the values of X_{δ_e}, Z_{δ_e}, and M_{δ_T} were set to zero so that the Table 1 approximate factors were applicable. The configuration details are given in Table 2, and the pilot rating data obtained are shown in Fig. 2. The pilots were instructed specifically to use throttle as the primary h control for the data shown. Additional runs were also made using θ_c as the primary h control,[13] but for the backside conditions of interest here these all produced worse ratings than those shown. The purpose of the ensuing analysis and discussion is to illustrate how the problem area criteria already set forth explain the data trends.

Analysis

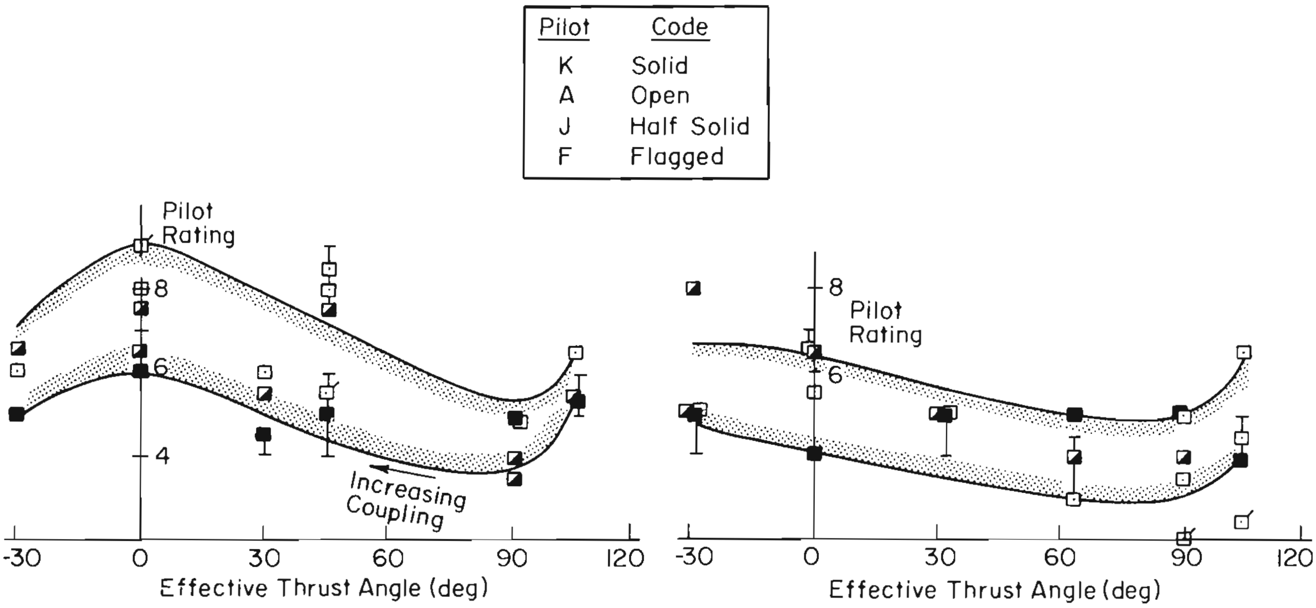
Considering θ_c as the effective stick input and recognizing the previously noted effects of high θ-loop gain, the applicable transfer functions for

TABLE 2. TEST CONFIGURATIONS AND RANGE OF VARIABLES [a]

CONDITION NO.	DENOMINATOR		ATTITUDE RATE NUMERATOR [b]		SPEED NUMERATOR [b]		THROTTLE SENSITIVITY	THRUST ANGLE ARC TAN	X_w
	$1/T_{\theta_1}$ (ζ_θ)	$1/T_{\theta_2}$ (ω_θ)	ATTITUDE $1/T_{h_1}$	THROTTLE $1/T_{h_\theta}$	ATTITUDE $1/T_{u_1}$	THROTTLE $1/T_{u_\theta}$	$Z_{\delta_T}/X_{\delta_T}$ g/in.	$-Z_{\delta_T}/X_{\delta_T}$	
1	.1	.5	−.09	0	.5	.5	−.146/−.0363	104	0
2	↓	↓	↓	.1	↓	NA	−.15/0	90	↓
3				.5		.5	−.106/.106	45	
4				.79		↓	−.075/.13	30	
5				NA			0/.15	0	
6				−.59			.075/.13	−30	
7	.3	.3	−.03	0	.73	.9	−.146/−.0363	104	.1
8	↓	↓	↓	.1	↓	NA	−.15/0	90	↓
9				.3		.3	−.134/.067	63.5	
10				.79		.44	−.075/.130	30	
11				NA		.50	0/.150	0	
12				−.59		.56	.075/.13	−30	

[a] Dynamic characteristics valid for perturbation about 60 kt trim condition; $X_u = -0.10$; $Z_w = -0.50$; $Z_u = -0.40$.

[b] NA in the limit when either X_δ or Z_δ are zero and the time constant is undefined, i.e., for $\theta_T = 90^\circ$, $N^u_{\delta_T} = X_{\delta_T}[s + (1/T_{u_\theta})] = X_w Z_{\delta_T}$; for 0°, $N^h_{\delta_T} = -Z_{\delta_T}[s + (1/T_{h_\theta})] = -Z_u X_{\delta_T}$.



a) Extreme Backside, $1/T_{h_1} = -.09$
Decoupled $N^{\theta}_{\delta_e}(1/T_{\theta_1} \neq 1/T_{\theta_2})$

b) Moderate Backside, $1/T_{h_1} = -.03$
Coupled $N^{\theta}_{\delta_e}(1/T_{\theta_1} = 1/T_{\theta_2})$

Figure 2. Effect of Various Control and Configuration Characteristics on Manual STOL Mode Path Control (Ref. 13)

$\dot{h}$ and u control are then those already given for the attitude constrained situation (Eqs. 13-17). Using these, the pertinent coupling numerators (see Table 1) and assuming θ_{CF} = steady-state θ_{CF_o}[§§]:

$$\left.\frac{\dot{h}}{\delta_T}\right]_{\theta_{CF}} = \frac{-Z_{\delta_T}\left(s+\frac{1}{T_{h_\theta}}\right) - \theta_{CF}Z_\alpha\left(s+\frac{1}{T_{h_1}}\right)}{\left(s+\frac{1}{T_{\theta_1}}\right)\left(s+\frac{1}{T_{\theta_2}}\right) \equiv \Delta'}$$

$$= \frac{-Z_{\delta_T}\left(1+\frac{\theta_{CF}Z_\alpha}{Z_{\delta_T}}\right)}{\Delta'}\left[s + \frac{\frac{1}{T_{h_\theta}} + \frac{\theta_{CF}Z_\alpha}{Z_{\delta_T}}\left(\frac{1}{T_{h_1}}\right)}{1+\frac{\theta_{CF}Z_\alpha}{Z_{\delta_T}}}\right] \tag{25}$$

$$= \frac{A_h'}{\Delta'}\left(s+\frac{1}{T_{h_{\theta_{CF}}}}\right)$$

where

$$\theta_{CF} \equiv \left(\theta_{CF_o}\right)_{s=o} = -\left.\frac{X_{\delta_T}\left(s+\frac{1}{T_{u_\theta}}\right)}{\left(X_\alpha - g\right)\left(s+\frac{1}{T_{u_1}}\right)}\right]_{s=o}$$

$$= -\frac{X_{\delta_T}T_{u_1}}{(X_\alpha - g)T_{u_\theta}}$$

$$\theta_{CF}\frac{Z_\alpha}{Z_{\delta_T}} = -\frac{X_{\delta_T}Z_\alpha T_{u_1}}{Z_{\delta_T}(X_\alpha - g)T_{u_\theta}} \doteq -\frac{X_{\delta_T}Z_\alpha\left(-Z_w + \frac{Z_{\delta_T}}{X_{\delta_T}}X_w\right)}{Z_{\delta_T}\left(X_\alpha - g\right)\left(\frac{gZ_w}{X_\alpha - g}\right)} \tag{26}$$

$$= \frac{X_{\delta_T}}{Z_{\delta_T}}\frac{Z_\alpha}{g} - \frac{X_\alpha}{g}$$

$$\left.\frac{u}{\theta_c}\right]_{\substack{h \to \delta_T \\ \theta_{CF}}} = \frac{\left(X_\alpha - g\right)\left(s+\frac{1}{T_{u_1}}\right) + \frac{Y_{P_h}}{s}\left[X_{\delta_T}Z_\alpha - Z_{\delta_T}\left(X_\alpha - g\right)\right]}{\Delta' + \frac{Y_{P_h}}{s}\left.N_{\delta_T}^{\dot{h}}\right]_{\theta_{CF}} \equiv \Delta''}$$

$$= \frac{\left(X_\alpha - g\right)\left\{s^2 + \frac{s}{T_{u_1}} - Y_{P_h}Z_{\delta_T}\left[1 - \frac{X_{\delta_T}Z_\alpha}{Z_{\delta_T}(X_\alpha - g)}\right]\right\}}{s\Delta' + Y_{P_h}\left.N_{\delta_T}^{\dot{h}}\right]_{\theta_{CF}} \equiv \Delta''} \tag{27}$$

$$= \frac{A_u'\left[s^2 + 2\zeta_1\omega_1 s + \omega_1^2\right]}{\left(s+\frac{1}{T_{u_1}'}\right)\left[s^2 + 2\zeta_2\omega_2 s + \omega_2^2\right]}$$

Based on the foregoing relationships, the $\dot{h}/\delta_T]_{\theta_{CF}}$ transfer functions were computed for the conditions and parameters of Table 2. The resulting h loop was then closed with a pure gain pilot, $Y_{P_h} = K_h$, adjusted to give a high-frequency asymptotic crossover of 0.5 rad/sec; i.e., $-K_hZ_{\delta_T}(1 + \theta_{CF}Z_\alpha/Z_{\delta_T}) = 0.5$. The resulting Δ'' characteristics were a low-frequency first-order pole almost equal to the first-order $\dot{h}/\delta_T\ _{\theta_{CF}}$ zero, and a second-order oscillation with a (closed-loop) frequency, ω_2, for all conditions, of about 0.72 ± 0.02 rad/sec, and a damping ratio of about 0.32 ± 0.06. The same values of $Y_{P_h} = K_h$ used to obtain Δ'' yielded similar second-orders for the $u/\theta_c]_{h \to \delta_T,\ \theta_{CF}}$ numerators (i.e., ω_1 = 0.71 rad/sec, ζ = 0.35 for Conditions 1-6 and ω_1 = 0.86 rad/sec, ζ = 0.42 for Conditions 7-12). Similar "tracking" of closed-loop poles and zeros is also observed in Ref. 8 where it is shown to be true in general; such generic developments have not yet been attempted in the present instance. At any rate, the similar second orders cancel approximately, leaving only a low-frequency first-order pole for $u/\theta_c|_{h \to \delta_T,\ \theta_{CF}}$, shown in Table 3, together with other pertinent computational results now to be examined.

Discussion

Starting with zero thrust inclination (Conds. 5 and 11), the notion of crossfeed seems most appropriate, because pilots "naturally" pull the nose up when adding power (to reduce speed excursions and achieve a faster final climb rate). The magnitude of the crossfeed which appears quite high (0.15-0.16 rad/in. of throttle) is in fact reasonable in terms of the corresponding attitude/speed value. That is, one inch of throttle produces a steady-state u increment (see Eq. 16) of $X_{\delta_T}T_{\theta_1}T_{\theta_2}/T_{u_\theta}$ = 48.4 fps ≐ 29 kt, so that a θ_{CF} = 0.15 rad/in. = 8.6 deg/in. converts to about 0.3 deg/kt. On this basis, the magnitudes of all other crossfeeds, except those which are negative, also appear reasonable.

The negative crossfeeds (Conditions 1, 7, and 8) go counter to the pilot's inherent training and are almost instinctively disliked. Also, even if used, they conflict with the primary task, as evidenced by the reduced net altitude gain, A_h'. On these two counts the conditions requiring negative crossfeed should be among the worst tested, which they are (Fig. 2a at 104 deg; Fig. 2b at 90 deg, 104 deg). On the other hand, those conditions requiring zero or small positive crossfeeds (i.e., Fig. 2a at 90 deg for the extreme, and Fig. 2b at 63.5 deg for the moderate, backside condition) are the best tested.

In connection with these last two conditions, 2 and 9 respectively, note that although the altitude bandwidths are about the same, the speed

[§§]For all the experimental conditions in Table 2, the ratio of the 3 sec to the steady-state value of $\theta_{CF}(t)$ lies between 0.89 and 1.16, i.e., roughly constant. Crossfeed is therefore considered to be reasonable in this sense, as discussed earlier.

TABLE 3. COMPUTED CLOSED-LOOP PARAMETERS AND PROPERTIES

	COND.	THRUST ANGLE (deg)	θ_{CF} (rad/in.)	gK_h (in./ft)	$\frac{A'_h}{g}\left(\frac{1}{T_{h_{\theta_{CF}}}}\right)$ [a]	ω_h [c]	$\left(\frac{1}{T'_{u_1}}\right)$ [b]	ω_u [c]	$\left(-\frac{u}{\theta}\Big]_{\substack{h \to \delta_T \\ \theta_{CF}}}\right)$ steady-state (fps/rad)
Extreme backside, $\frac{1}{T_{h_1}} = -.09$; Decoupled $N^{\theta}_{\delta_e}\left(\frac{1}{T_{\theta_1}} \neq \frac{1}{T_{\theta_2}}\right)$	1	104	−.0363	5.69	.088(.06)	.60	.06	.06	52.2
	2	90	0	3.33	.15 (.10)	.50	.10	.10	31.3
	3	45	.106	1.81	.276(.137)	.42	.14	.14	22.4
	4	30	.13	1.77	.283(.144)	.40	.15	.15	20.9
	5	0	.15	2.09	.239(.260)	.19	.28	.28	11.2
	6	−30	.13	3.77	.133(.192)	.33	.21	.21	14.9
Moderate backside, $\frac{1}{T_{h_1}} = -.03$; Coupled $N^{\theta}_{\delta_e}\left(\frac{1}{T_{\theta_1}} = \frac{1}{T_{\theta_2}}\right)$	7	104	−.0665	12.8	.039(.082)	.60	.073	.07	42.0
	8	90	−.0326	5.14	.098(.17)	.49	.163	.16	18.8
	9	63.5	.041	2.52	.199(.192)	.44	.19	.19	16.1
	10	30	.150	1.91	.262(.202)	.42	.20	.20	15.3
	11	0	.157	2.02	.247(.213)	.41	.21	.22	14.6
	12	−30	.117	3.03	.165(.229)	.38	.23	.23	13.3

a $$\frac{\dot{h}}{\delta_T}\Big]_{\theta_{CF}} = \frac{A'_h\left(s + \frac{1}{T_{h_{\theta_{CF}}}}\right)}{\Delta'}$$

Conds. 1-6: $\Delta' = (s + .1)(s + .5)$

Conds. 7-12: $\Delta' = (s + .3)(s + .3)$

b $$\frac{u}{\theta_c}\Big]_{\substack{h \to \delta_T \\ \theta_{CF}}} = \frac{A'_u\left(s^2 + 2\zeta_1\omega_1 + \omega_1^2\right)}{\left(s + \frac{1}{T'_{u_1}}\right)\left(s^2 + 2\zeta_2\omega_2 s + \omega_2^2\right)}$$

$\omega_2 \doteq .72$, $\zeta_2 \doteq .32$

Conds. 1-6: $\omega_1 = .71$, $\zeta_1 = .35$, $A'_u/g = -1$

Conds. 7-12: $\omega_1 = .86$, $\zeta_1 = .42$, $A'_u/g = -.67$

c The ω_h, ω_u values are the 45 deg phase margin frequencies for the above two transfer functions, respectively.

bandwidth## for Condition 9 is about twice that for Condition 2; but there is still resonable separation (a factor of 2) between the secondary u and primary $\dot{h}$ responses for Condition 9. The faster u response and the increased stiffness in u (increasing $1/T'_{u_1}$ is akin to increasing X_u) for Condition 9 (63.5 deg, moderate) apparently is responsible for the somewhat improved ratings, over Condition 2 (90 deg, extreme) shown in Fig. 2.

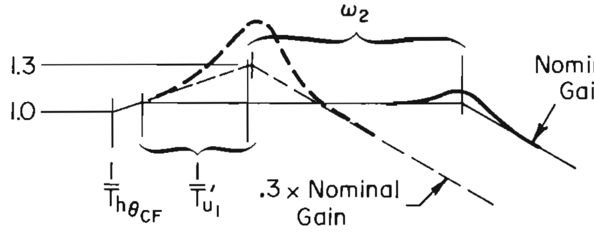
Notice that moderate Conditions 9-12, for thrust angles between 63.5 and −30 deg show a progressive reduction in ω_h and in the separation between ω_h and ω_u. On both counts, the ratings should gradually degrade with decreasing thrust incidence, and this trend is evident in the Fig. 2b data.

##These bandwidths, ω_h and ω_u, are, respectively, inversely proportional to the dominant response time constant for the h response to a step, crossfed δ_T input, and for the u response to a step θ_c with $h/\delta_T]_{\theta_{CF}}$ closed at the K_h gains shown.

An outstanding example of the reduced separation between ω_h and ω_u is Condition 5 for extreme backside, 0 deg thrust inclination; in this instance, ω_u is greater than ω_h, which is quite low. Thus, not only are the normally expected primary and secondary response characteristics reversed, but the primary altitude response, by itself, appears deficient. However, the closed h loop characteristic $\equiv \Delta'' = [s + (1/T'_{u_1})](s^2 + 2\zeta_2\omega_2 s + \omega_2^2)$ shown in Table 3 as approximately constant for all conditions belies this apparent poor altitude control. This conflict in interpretation is resolved by considering the effects of K_h variations on the resulting closed h loop response characteristics. For instance, reducing K_h to three-tenths the value listed in Table 3 results in a decreased value of ω_2 as expected, but produces a disproportionate increase in the value of $1/T'_{u_1}$ for Condition 5. (For other conditions the value of $1/T'_{u_1}$ varies only slightly for similar gain changes.)

The nature of the specific changes for Condition 5 is illustrated in the tabulations and sketch shown below.

Gain	$\frac{1}{T_{h_{\theta_{CF}}}}$	$\frac{1}{T'_{u_1}}$	ω_2	ζ_2	ω_1	ζ_1
Nominal (Table 3)	.260	.28	.72	.32	.71	.35
0.3 × Nominal	.260	.34	.34	.39	.39	.64



Sketch Showing Bode Amplitude for

$$\frac{h}{h_c} \sim \frac{s + \frac{1}{T_{h_{\theta_{CF}}}}}{\left(s + \frac{1}{T'_{u_1}}\right)\left(s^2 + 2\zeta_2\omega_2 s + \omega_2^2\right)}$$

It is apparent that a reduction in gain tends to produce an h overshoot in the frequency range of interest for control. The peak sketched corresponds to an effective (closed-loop) ζ of about 0.29, which produces about a 35% overshoot to a step input (in h_c). As noted earlier, Condition 5 is considerably more sensitive in this regard than the other conditions surrounding it. In the sense then that it is connected with such gain sensitivity, the originally noted poor ω_h shown in Table 3 can be taken as an indication of a piloting problem.

Finally, and still considering Condition 5, it is shown in Table 3 as having the lowest closed-loop u/θ steady-state response. It appears, for all these reasons, that Condition 5 is the worst of all those tested. Again, the data trends reflect this analytically-derived conclusion.

Example 3.

We here examine a particular configuration (J4) taken from the Ref. 29 investigation to illustrate another facet of "backside" problems. In this instance, the backside, negative value of $1/T_{h_1}$ is also accompanied by a negative value of $1/T_{\theta_1}$; the closed-loop implications of the latter are the specific purpose of the example analyses to be presented.

The objective of the referenced investigation was to examine flight path stability requirements as represented by boundary values [10] of $(d\gamma/du)(\text{deg/kt}) = -3/T_{h_1}$. To obtain the desired large positive values of $d\gamma/du$ (negative values of $1/T_{h_1}$), a "basic" configuration was degraded by effectively varying X_w and X_u. In this process, the more negative values of $1/T_{h_1}$ also resulted in negative values of $1/T_{\theta_1}$, in accordance with the approximate Eq. 18 relationship.

From the standpoint of open-loop characteristics, negative $1/T_{\theta_1}$ results in steady-state attitude-to-elevator responses which are reversed from the norm. That is, up elevator produces, eventually, a nose-down attitude, although the initial response is correct (nose up). Hence, the aircraft is not easily trimmable, and the pilot starts with a net "burden" represented by poor unattended characteristics.

The negative value of $1/T_{\theta_1}$ therefore presents an immediate problem relative to the basic, inner, attitude loop integrity, as may be inferred in more detail from the system survey given in Fig. 3 for the example case. This figure displays, upper left, the basic block diagram and the pertinent open-loop airplane and pilot model transfer functions. The transfer functions are presented in an abbreviated notation where the leading number is the airplane gain, the single numbers in parentheses represent first-order factors, i.e., $(1/T)$ corresponds to $[s + (1/T)]$, and the double numbers represent second-order factors, i.e., (ζ, ω) corresponds to $s^2 + 2\zeta\omega s + \omega^2$. The lower left portion of the figure is a conventional root locus for increasing (pilot) gain. The right portion of the figure is a combined $s = j\omega$ and $s = -\sigma$ Bode root locus plot for the complete open-loop (upper left) transfer function. The $j\omega$ Bode is fairly standard with amplitude and phase shown by light solid lines and amplitude asymptotes and breakpoints shown dashed. The dotted lines show how the second-order poles are altered by increasing open-loop (pilot) gain, ω'_p decreasing and ω'_{sp} increasing; the corresponding changes in ζ'_p and ζ'_{sp} are "spotted" along the applicable dotted trajectories. The heavy solid σ Bode lines labeled $G(-\sigma)$ and $G(\sigma)$ show how, as gain increases, the first-order poles in the closed-loop characteristic appear in the left and right planes, respectively, of the conventional root locus. For example, following the ω'_p migrations on both the Bode and conventional root loci, as gain increases, ω'_p decreases and ζ'_p increases, becoming unity when the dotted Bode trajectory intersects the $G(-\sigma)$ line. The gain at which this occurs corresponds to the horizontal slope of $G(-\sigma)$, about −12 dB. Continuing to increase gain decouples ω'_p into two

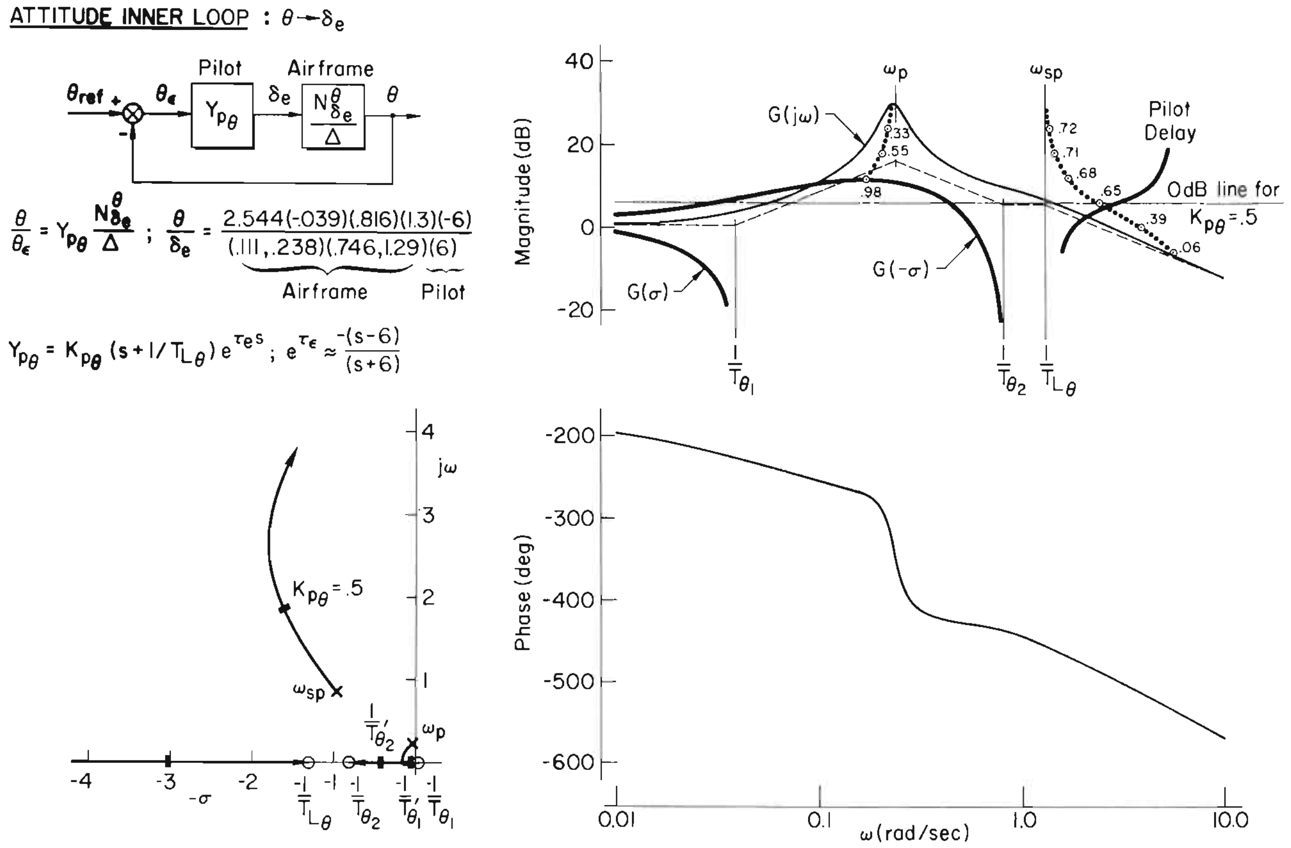


Figure 3. Attitude Loop System Survey

first orders, labeled $1/T'_{\theta_1}$ and $1/T'_{\theta_2}$ which, for further gain increases, migrate toward $1/T_{\theta_1}$ and $1/T_{\theta_2}$, respectively. For $K_{p_\theta} = 0.5$ the closed-loop poles shown as square symbols on the conventional root locus are also reflected as the intersections of the appropriate gain line with the dotted (second-order) and solid $G(-\sigma)$ Bode root locus lines. For $K_{p_\theta} > 1$, the value of $1/T'_{\theta_1}$ is negative as reflected by a gain line intersection with $G(+\sigma)$. Thus, the Bode root locus format displays all the pertinent closed-loop information needed directly as a function of gain; whereas the conventional root locus, although directly displaying the root trajectories, requires additional computations to locate the roots as a function of specific gains.

Examining Fig. 3 in detail, it may be seen first that the pilot model has been "adjusted" to include moderate lead ($T_{L_\theta} \doteq 0.77$ sec) and a corresponding time delay, $e^{-.33s}$, represented by its Pade approximant, $-(s - 6)/(s + 6)$. The lead is required to reduce the phase lag in the region of desirable crossover frequencies ($\omega_{c_\theta} > 2$ rad/sec). For the assumed lead, and adequate gain and phase margin, crossovers up to about 3 rad/sec are possible for a corresponding $K_{p_\theta} \doteq 1.0$. At this gain, very low-frequency attitude "wandering" would still appear in θ/θ_c, because the closed-loop $1/T'_{\theta_1}$ pole would correspond essentially to a free s; i.e., θ would ramp off at a low rate, as would the u response to θ_c, i.e., $u/\theta_c = (u/\theta)(\theta/\theta_c)$.

Increased gain requires increased T_{L_θ} (to avoid short-period instability) which tends to increase the pilot's workload and degrade his opinion. However, even neglecting this aspect, the results are still unfavorable. That is, increased gain (over $K_{p_\theta} = 1$) pushes $1/T'_{\theta_1}$ into the right half root locus plane, so that the ramping responses now become divergent.

Reducing the gain (e.g., to $K_{p_\theta} = 0.5$), as shown in Fig. 3) sacrifices some of the desired bandwidth but eliminates the slow ramping or divergent tendencies. However, the steady-state θ response is now reversed, as for the bare (open-loop) airplane. Also, for ±6 dB variation about this nominal gain, the closed-loop properties change over a range from those described above for $K_{p_\theta} = 1$, to a condition where the path modes ($1/T'_{\theta_1}$, $1/T'_{\theta_2}$) become coupled (at ω'_p), undesirable (as noted earlier) from the standpoint of separating u and $\dot{h}$ responses.

In effect, the pilot has no good adjustment possibilities for what is normally a simple and fundamental loop closure. If he sacrifices attitude bandwidth (low gain), he also incurs $\dot{h}$ and u response coupling and poor low-frequency attitude regulation, all bad. If he increases bandwidth (high gain), he gets low-frequency attitude and speed divergence. He is "boxed in" by conflicting and/or compounding effects represented by extreme sensitivity to his exact "adjustments," and stemming basically from poor inherent speed stability (i.e., $1/T_{\theta_1} \doteq -X_u < 0$). In a sense, then, the pilot has little choice but to regulate also on speed, as illustrated in Fig. 4 for a "nominal" attitude gain, K_{p_θ}, of 0.5. This loop can be easily closed at frequencies up to a little more than 1 rad/sec. Such large crossovers and attendant high gain would, however, reduce the

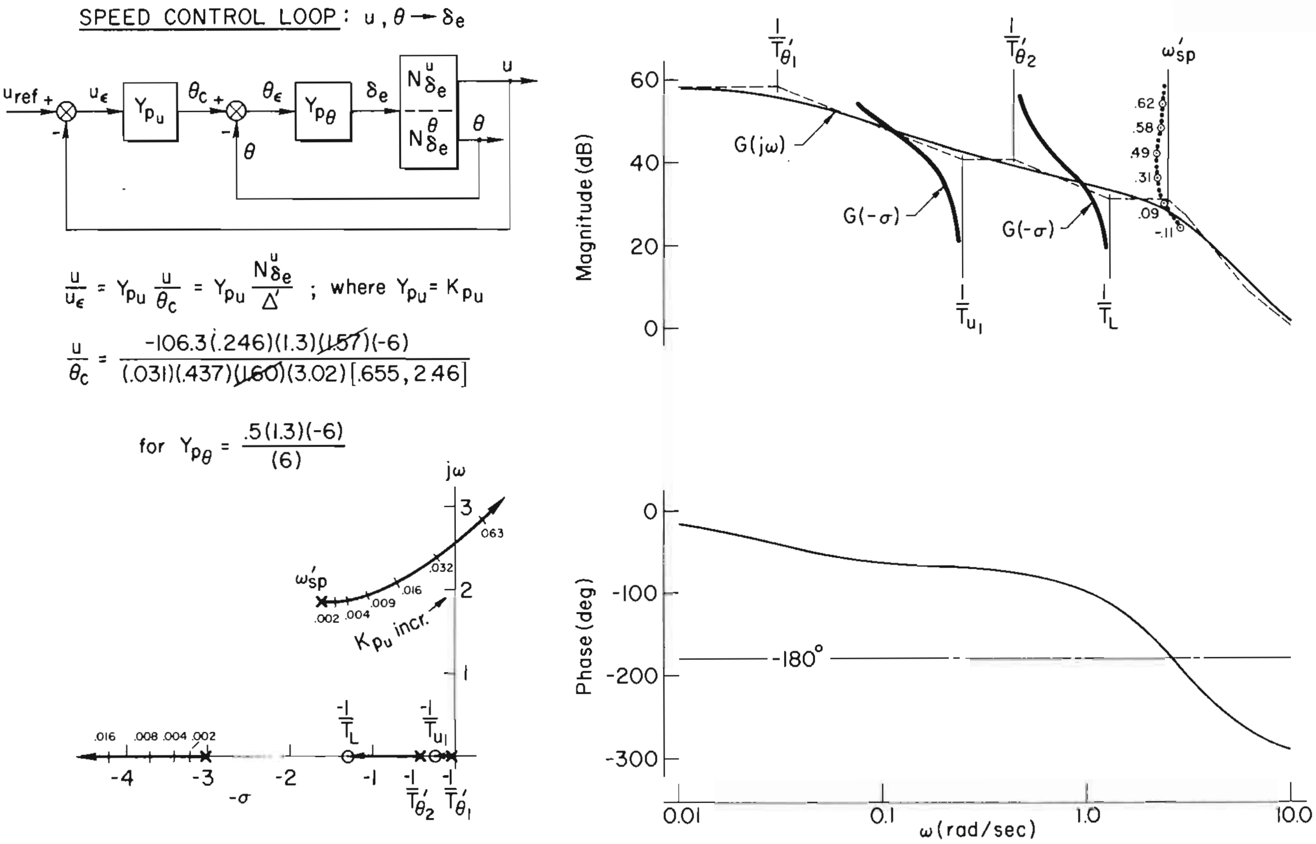


Figure 4. Speed Control with Relatively Loose Attitude Control; u, θ → δ_e

short-period damping ratio considerably (from 0.655 to about 0.3) and thereby further compound the attitude loop problem. For lower, more normal, crossovers, around 0.3 rad/sec, the reduction in ζ_{sp} to about 0.50 seems tenable. However, the attitude loop, normally regarded as fundamental, is now subservient to the relatively low bandwidth speed control loop. In fact, speed control governs the overall stability margin in this multiloop system; thus, the integrity of the attitude control is lost.

Also, the fact that u/θ_c must be closed for good regulation represents a violation of the control economy concept. Remember the first example, where it was noted that u excursions were ordinarily quite small for the STOL mode (nominally appropriate here because of the backside condition) even if u were not controlled at all. For the present example, not only must the u loop be closed, but it becomes just as important as the θ loop, thereby also violating desirable control hierarchy. That is, both attitude and u control actions are intertwined so that increased pilot attention and concentration is required.

The fact that the u loop must be closed is traceable to the quasi-divergent or ramping behavior of the u responses noted earlier. Such behavior represents poor speed "indexing" with attitude, which is always undesirable for both regulatory and trim management control. Good indexing means that a given discrete secondary input results in a predictable final value attained in a reasonable time (5-10 sec). In effect, good indexing is akin to constant gain over an adequate bandwidth (0.1 to 0.2 rad/sec). A glance at Fig. 4 shows that the u/θ_c indexing for this example is deficient in that the final value is slowly attained ($1/T'_{\theta_1}$) and is extremely sensitive to the θ_c input (high u/θ_c dc gain).

In conclusion, this example illustrates, without considering the additional problems directly associated with negative "static" flight path stability, $1/T_{h_1}$, many of the regulatory and response problems noted in Section II. The particular deficiencies observed, which stem specifically from poor control of attitude and speed undoubtedly contribute heavily to the recorded Cooper-Harper pilot rating of about 7-1/2.[29]

Example 4

The final example considers "frontside" conditions which have inherently coupled path modes due to large positive X_α. As previously indicated, such conditions may result from airplane augmentation utilizing an angle-of-attack autothrottle. In fact, this example is based largely on the analysis of autothrottle-associated problems given in Ref. 8. Basically, the referenced study illustrated and confirmed how this "coupling" caused regulatory control problems during carrier approach flight operations.

One of the specific primary control problems repeatedly encountered in the referenced study centered on loss of flexibility in the pilot's ability to trim airspeed when an off-nominal condition occurred (discussed in Section II). With the autothrottle engaged, no direct manual throttle input was possible for the U.S. Navy aircraft studied; in fact, all throttle or thrust activity was effectively keyed to elevator or attitude changes. This is consistent (as previously noted) with pilots' conventional use of attitude to exchange airspeed and altitude.

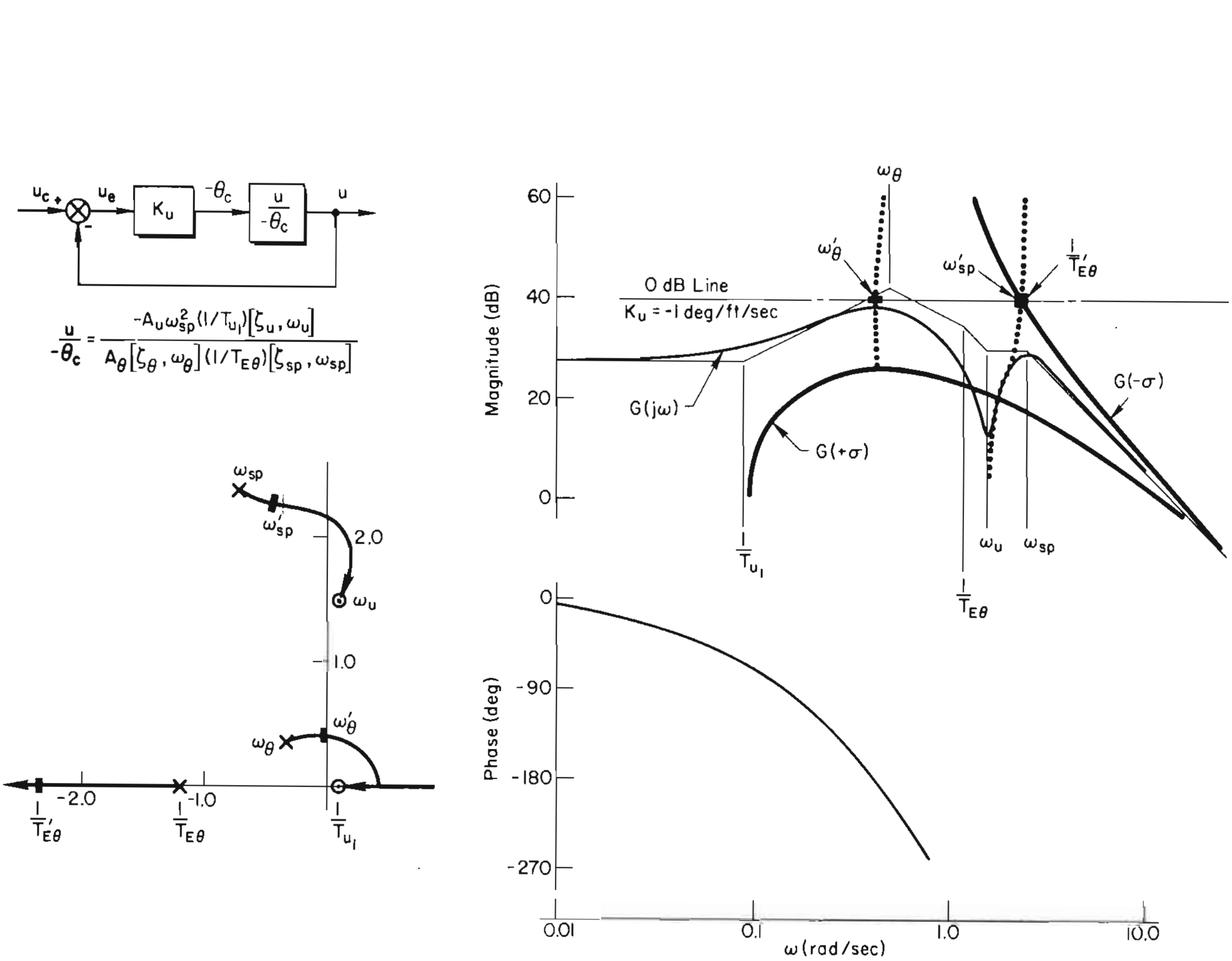


Figure 5. System Survey of Closed-Loop Airspeed Control with Attitude

The generic aspects of the speed control problem with autothrottle engaged have already been discussed in Section II; specifically, it was noted there that the u/θ_c response given by:

$$\frac{A_u'\left(s + \frac{1}{T_{u_1}}\right)}{\left[s^2 + 2\zeta_\theta\omega_\theta s + \omega_\theta^2\right]}$$

was oscillatory (due to ω_θ) and delayed (due to negative $1/T_{u_1}$). These generic properties are also evident in the specific-aircraft system survey given in Fig. 5 (taken directly from Ref. 8); the transfer function shown reflects the full complement of poles and zeros obtained when simplifying assumptions are not used and thrust lag is included.

An examination of Fig. 5 shows that the closed-loop system is neutrally stable ($\zeta_\theta' = 0$) for moderate gain (i.e., 1 deg/fps) and that even for this gain level there is no effective regulation of airspeed. In fact, the effective closures are limited by potential instabilities, at ω_θ' and ω_{sp}', to gains which are above those for a crossover condition. The nonexistent bandwidth, the poor closed-loop stability for reasonable gains, and the low-frequency droop infer low effective path damping and poor speed regulation with large attendant attitude excursions, all confirmed by the associated pilot comments as reported in Ref. 8. It appears that airspeed regulation with attitude is infeasible, and the pilot has therefore lost ability to regulate speed.

The foregoing conclusion is based on the use of only attitude (or associated elevator) inputs. It is logical to assume that given the use of the throttle the pilot could regain speed control. Unfortunately, this is not the case, because the coupling condition magnifies $\dot{h}$ relative to u responses for θ_c inputs; and the resulting net u/θ_c gain with $\dot{h}$ constrained is small (Eq. 22).

Such specific situations, i.e., stick and throttle control for coupled, frontside conditions, were tested in the Ref. 13 investigation, previously exposed in Example 2. The results given in Fig. 6

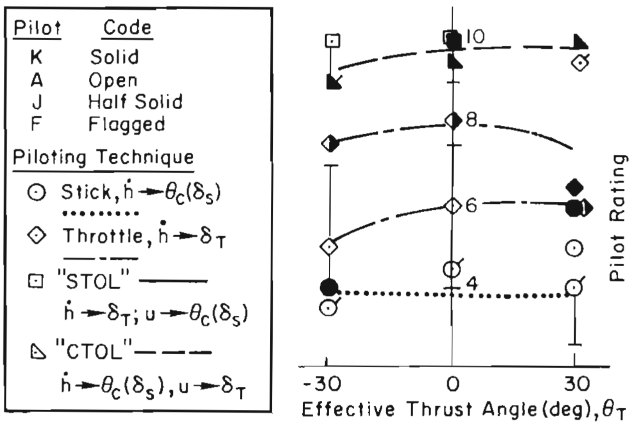


Figure 6. Effect of Control Techniques on Pilot Rating with Strong "Dynamic" Coupling (ζ_θ = 0.6, ω_θ = 0.5; $1/T_{h_1}$ = +0.21)

show that only stick control of flight path through attitude commands (i.e., $\dot{h} \rightarrow \theta_c(\delta_s)$ is nearly satisfactory (i.e., PR $\doteq$ 4); the pilots simply accepted the resulting (relatively small) airspeed excursions, while complaining about the loss of speed control. Attempts to use partitioned multi-loop dual-control modes [e.g., $\dot{h} \rightarrow \theta_c(\delta_s)$, $u \rightarrow \delta_T$ or $\dot{h} \rightarrow \delta_T$, $u \rightarrow \theta_c(\delta_s)$] resulted in unacceptable-to-uncontrollable situations (i.e., PR $\doteq$ 10) because of the extreme coupling. Single-loop throttle control (i.e., $\dot{h} \rightarrow \delta_T$) was regarded as unacceptable in general. These results are consistent with the analytically derived expectations given in Section II.

IV. Summary and Conclusions

Approach path piloting techniques and experimentally-observed problem areas have been explored through application of pilot/vehicle analysis methods. Results have demonstrated that there are a large number of rules and/or aircraft parameters which must be considered in delineating "good" from "bad" handling qualities. The methodology and analytical considerations applied and described afford the basic framework for a systematic, logical, and effective design and specification procedure.

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