An Analysis of Navy Approach Power Compensator Problems

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The current design concept of Naval aircraft Approach Power Compensator Systems (APCS) is briefly described. Problems with this concept are identified from flight test reports as being associated with flight path control and inappropriate thrust responses. Aircraft responses with an APCS are contrasted to those without, thereby demonstrating certain fundamental, and not always beneficial, changes in the response characteristics in the low and intermediate frequency range. Parameters descriptive of those responses are shown to depend upon not only the APCS parameters (e.g., gains) but also certain unalterable (by the APCS designer) aircraft characteristics. Among these are the rapidity of the engine's thrust response, the thrust vector inclination, and the heave damping (Z_w) of the aircraft.

Introduction

THE use of Approach Power Compensator Systems (APCS) in the Navy dates back at least ten years. During this interval the state of the art has evolved to increasing levels of sophistication in the choice of basic feedbacks, their mixing, and the equalization (often nonlinear) used. These systems have the purpose of relieving the pilot of the throttle management task during all phases of carrier approach. This is particularly important on modern jet aircraft whose characteristics at approach speed are relatively unforgiving, thereby making the pilot's task quite demanding. The throttle (or thrust) management function is also essential to approaches with the Automatic Carrier Landing Systems (ACLS).

This paper presents some of the key results of a study of Navy Approach Power Compensator Systems,§ fully documented in Ref. 1. In particular, certain deficiencies in these systems' performance (as evidenced by both pilot commentary and objective performance measures) are correlated with changes in the dynamics of the APCS-equipped aircraft from that of the aircraft without an APCS. In brief, the APCS acts not only as a regulator of airspeed (as intended), but also as an augmentor of the aircraft's flight path responses. Not all aspects of such augmentation are desirable.

Description of Current APCS

The general features of the control laws for the current Navy APCS concept are defined in the functional block diagram of Fig. 1. The basic relations expressed by this diagram involve feedbacks (and associated equalization) of sensed angle of attack (α), normal acceleration (n_z), and (sometimes) feedforward of elevator deflection (δ_e) to the throttle (δ_T). The engine thrust response dynamics are a part of the airframe characteristics. The airframe may include a stability augmentation system (SAS). The APCS is required[2] to control both airspeeed and angle of attack for pilot (or ACLS) control inputs and external (gust) disturbances.

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Problem Areas

The problems with this concept were identified by reviewing the literature (chiefly flight evaluation reports,[3-10]) and through conversations with personnel of the Naval Air Test Center, Patuxent River, Md. Most are recurrent, that is, associated with several different aircraft types, and all are in the form of undesired or inappropriate responses of the APCS-equipped aircraft to various situations. In this paper attention is confined to those problems pertinent to closed-loop control of flight path by the pilot (or ACLS). These are listed in Table 1.

In closed-loop control, the pilot (or ACLS) is functioning in either a command or regulatory control sense. Command control refers to situations involving a change from one reference to another such as glide slope acquisition, initial line-up, or exit from a turn. Problems in this category (the first grouping of Table 1) stem from an inability to make precise changes in flight path without over- (or under-) shoots in airspeed, angle of attack, thrust, or encountering stall. Regulatory control refers primarily to maintaining precision control of glide slope with or without external disturbances (e.g., the "burble" aft of the carrier's ramp). Problems in this category are listed in the second grouping of Table 1. The central factor here is the loss of flexibility—where he formerly had two controls at his disposal (throttle and elevator) the pilot of an APCS-equipped aircraft now has only one (elevator).

The loss of flexibility implies changes in the piloting technique. Reference 11 points out that in approaches where the pilot controls the throttle setting, his use of throttle (and elevator) depends not only on airspeed error, but also on flight situation (e.g., high or low at glide slope acquisition or in close to the ramp). From a control function viewpoint, the throttle has three roles: indexing to reduce steady-state

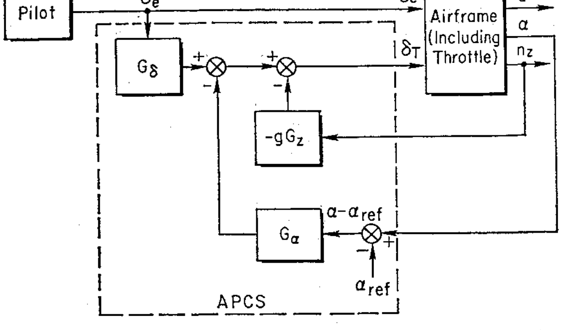

Fig. 1 Navy APCS functional block diagram.

Table 1 Flight path control problems with APCS-equipped aircraft

APCS problem description	General remarks and commentary
1. Acquisition and turn maneuvers	
a) Excessive α deviation and airspeed changes during turn entry and exit.	a) To hold fixed α (as in level flight) requires increased airspeed in the turn. The additional lift required must initially be provided by increased α, as the aircraft cannot accelerate instantaneously. On turn exit, the APCS should rapidly reduce the airspeed error to minimize difficulties in acquiring the glide slope.
b) Inability to acquire glide slope rapidly without excessive α and airspeed errors accompanied by thrust surges.	
c) Excessive throttle motion and thrust loss during tipover.	b,c) "Good" closed-loop (pilot plus airframe/APCS) response and stability (damping) of all important motions to "large" commands, implies systems of low effective order and good damping in the frequency range near 1 rad/sec.
2. Control and regulation on glide slope	
a) Difficulty in making glide slope corrections for various off-nominal situations, e.g., high, low, high-fast, low-slow, etc.	a,b) APCS inherently reduces throttle management flexibility and resulting ability of pilot to adjust thrust for off-nominal situations and gusts or burble. Erratic throttle motion will undermine pilot confidence in APCS, particularly if it results in slow airspeed situations with low power settings. Limited auxiliary thrust control, obtained by nonlinear tailoring of elevator crossfeed, helps. This aspect critical in close (i.e., near ramp) when low and slow due to effects of burble.
b) Poor performance in burble with excessive α and airspeed errors, altitude loss, and delayed thrust response resulting in over-the-top and bolter.	
c) Excessive pitch attitude changes required for glide slope correction.	c) Tight control of glide path with elevator inherently involves large attitude changes (overshoots) for aircraft with low lift-slopes.
d) Excessive sensitivity, overcontrol tendencies; piloting technique critical.	d) "Smooth" and sometimes "fingertip" pilot control required.

airspeed and sink rate errors resulting from attitude correction maneuvers, anticipating transient changes in airspeed or angle of attack due to maneuvers or burble disturbances, and providing gross excess thrust for aborting the approach (waveoff) or stall prevention.

With automatically controlled throttles, on the other hand, the pilot must rely on the APCS for the proper thrust inputs, and quite often he must change to a more suitable technique to obtain acceptable APCS action. For example, in correcting from a high condition the pilot will cycle the stick as he pushes over to avoid the thrust loss which would otherwise occur. The cycling technique apparently works effectively on APCS's with elevator crossfeed because of the rectification action resulting from APCS (or engine) response nonlinearities.[1]

The foregoing considerations and examples serve to identify the APCS as an augmentor (albeit a poor one in some respects)

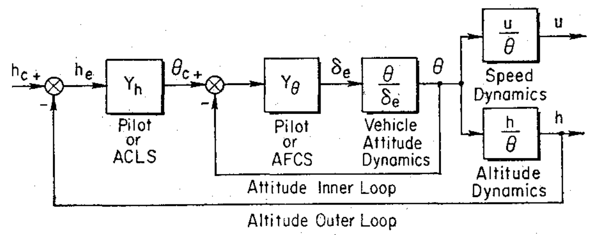

Fig. 2 Loop structure for flight path control.

of the aircraft's flight path responses to the pilot's corrective attitude changes. Our attention is therefore directed at identification of the changes in these responses and correction of the problems brought about by the APCS.

To show the connections between problems and dynamics as simply as possible, the major "recurring" problems associated with flight path control are examined in the following, using relevant example responses for a typical aircraft which shows crucial path control problems. The specific responses thus treated are altitude rate (or flight path angle) and airspeed to attitude commands.

Flight Path Control and Related Responses

The behavior of the aircraft in response to pilot (or ACLS) inputs for control of flight path angle (or altitude rate) is crucial for successful landing. Environmental considerations, chiefly the carrier's air wake or burble and the motions of the glide slope reference provided by the FLOLS (or ACLS), impose the need for frequent glide slope corrections (see Ref. 1 for a detailed environmental description).

In principle, flight path control can be considered primarily a task of controlling pitch attitude and altitude to provide the proper terminal conditions (airspeed, sink rate, attitude, etc.) at touchdown. Airspeed is maintained fairly constant by either the pilot or the APCS in controlling throttle position. In either case, the altitude control structure, assuming altitude control with attitude, may be represented by the multiloop system sketched in Fig. 2.

The elements are the pilot (or the ACLS plus coupler-AFCS), the inner attitude loop, and the outer-loop vehicle altitude dynamics. The related speed response is also indicated in Fig. 2. For this discussion we will briefly indicate the importance of the attitude inner loop and then go on to the resultant flight path or altitude rate and airspeed responses to attitude commands.

Pitch attitude control is important in its own right since it provides an essential, equalizing inner loop for altitude control. The feedback is, of course, pitch attitude to elevator (e.g., either by the pilot or suitable AFCS system). The pilot (or AFCS) in controlling vehicle attitude will tend to drive the low frequency poles of the system (open-loop modes of response) into the zeros of the attitude-to-elevator numerator, while driving the short-period response mode to higher frequencies. The new system characteristic polynomial (attitude-to-elevator loop tightly closed) approaches the attitude numerator zeros with adjustment for the short-period mode of response. Thus, using mixed notation¶

$$\Delta' \doteq N_{\delta_e}^{\theta}[\zeta_{sp}', \omega_{sp}'] \doteq (1/T_{\theta_1})(1/T_{\theta_2})[\zeta_{sp}', \omega_{sp}'] \quad (1)$$

where the single prime (′) denotes one loop being closed, in this case, attitude-to-elevator, symbolized by $\theta \rightarrow \delta_e$.

The characteristic modes of the system are now described by the attitude numerator zeros, which replace the conven-

¶ Throughout this paper, $A(s + 1/T)$ is written $A(1/T)$; $A[s^2 + 2\zeta\omega s + \omega^2]$ is written $A[\zeta, \omega]$. N_δ^x and Δ represent numerator and denominator polynomials, respectively.

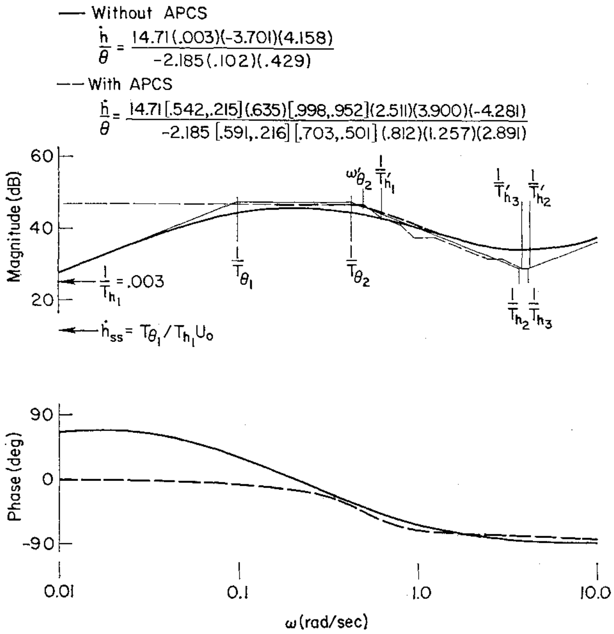

Fig. 3 Altitude rate response to pitch commands.

tional "phugoid," and the modified short-period mode. Consequently, the altitude rate response of the new system to pitch attitude commands can be approximated at low frequencies by neglecting the short-period response, that is

$$\dot{h}/\theta_c = N_{\delta_e}^{\dot{h}}/\Delta' \doteq N_{\delta_e}^{\dot{h}}/N_{\delta_e}^{\theta} = \dot{h}/\theta;\ \omega \ll \omega_{sp}' \tag{2}$$

Similarly, the speed response can be approximated by

$$u/\theta_c = N_{\delta_e}^{u}/\Delta' \doteq N_{\delta_e}^{u}/N_{\delta_e}^{\theta} = u/\theta;\ \omega \ll \omega_{sp}' \tag{3}$$

The approximations are valid for frequencies below that where the short-period mode contributes substantially to the gain and phase of the actual response. Both the altitude rate and airspeed responses to attitude commands, presuming a relatively tight attitude inner-loop closure, are given by the ratio of the pertinent numerators Eqs. (2) and (3) for frequencies substantially below the short-period mode. These expressions are indicative of the maximum performance capabilties (e.g., bandwidth and damping) of the resultant closed-loop systems (i.e., aircraft/APCS including either pilot or ACLS). Therefore, they provide a uniform basis, independent of the specific pilot or ACLS gains and equalization used in the inner-loop closure, for comparing the over-all effects and consequences of the APCS.

Altitude Rate (Flight Path Angle) Response

Path control without an APCS is relatively complicated because there is a variety of possible piloting techniques (e.g., h or $\dot{h} \to \delta_T$ or θ_c) which the pilot may choose to adopt; with an APCS the option of controlling thrust directly is removed. Accordingly, the most generally applicable technique, and that where differences with and without APCS are most apparent, is to control altitude with attitude. However, regardless of the technique, the governing criterion is adequate bandwidth in the path loop. "Adequate bandwidth" translates, in the time domain, as acceptable response in path-changing maneuvers, and good maintenance of the desired path in the presence of disturbances (e.g., burble). Both aspects of altitude control with attitude are examined below.

Bare Airplane Response

According to the Eq. (2) approximation, the response for conventional (no APCS) airplanes is given by

$$\dot{h}/\theta = A_h(1/T_{h_1})(1/T_{h_2})(1/T_{h_3})/A_\theta(1/T_{\theta_1})(1/T_{\theta_2}) \tag{4}$$

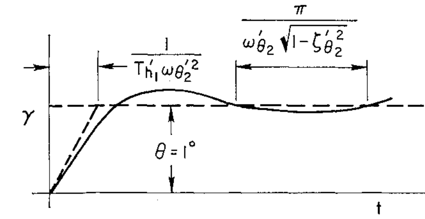

Fig. 4 Flight path response with APCS.

or, recognizing that $A_h/A_\theta T_{h_2}T_{h_3} \doteq U_0 Z_w \doteq U_0/T_{\theta_2}$; and for $\omega \ll |1/T_{h_2}|,\ |1/T_{h_3}|$:

$$\frac{\gamma}{\theta} \doteq \frac{(1/T_{h_1})}{T_{\theta_2}(1/T_{\theta_1})(1/T_{\theta_2})} \tag{5}$$

The initial response, characterized by the lag at $1/T_{\theta_2}$, later bleeds off or washes out with a time constant, T_{θ_1} (Eq. 5), to end up at a lower level given by the low-frequency Bode gain asymptote (Fig. 3), viz., $\gamma_{ss} = T_{\theta 1}/T_{h_1}$. Also depending on the rate of bleed-off given by T_{θ_1}, the response may never reach the value commended by the attitude change. This description neglects the effects of the net high frequency lag due to the short-period attitude response [Eq. (1)] and the zeros at $1/T_{h_2}$ and $1/T_{h_3}$. The latter zeros are associated with the so-called Z_δ effects that account for the initial rapid reversal in the altitude response to elevator (the elevator generates negative lift and an initial altitude loss to effect a nose-up attitude change).

The longer term response features are dominated by the airplane's losing speed and settling out at a new, increased rate of climb (flight path angle) which is, however, lower than initially "commanded." The zero at $1/T_{h_1}$ is often negative, whence the value of γ achieved is actually *below* the initial value as inferred in the Bode of Fig. 3. This means that the aircraft is operating on the backside (unstable) region of the thrust required vs airspeed curve and lacks speed stability.

The important points are that the initial flight path angle response is at a rate characterized by $1/T_{\theta_2}$ and the final response is given by the low to mid-frequency gain ratio, T_{θ_1}/T_{h_1}. Rapid response, i.e., a large value of $1/T_{\theta_2}$, is the key to good glide slope performance in the command and disturbance environment.[12] Contrariwise, low values of $1/T_{\theta_2}$ imply a sluggish response—to obtain a desired flight path angle change in a given time interval, the pilot will have to increase his attitude command. In the terminology of Table 1, "excessive" pitch attitude excursions are required for flight path response.

APCS-Equipped Airplane Response

With the APCS, the characteristic response, $\dot{h}/\theta$, is complicated by the many additional factors introduced by the APCS and engine response dynamics

$$\frac{N_{\delta_e}^{\dot{h}}]_{APC}}{N_{\delta_e}^{\theta}]_{APC}} = \frac{N_{\delta_e}^{\dot{h}} + G_\alpha N_{\delta_e\delta_T}^{\dot{h}\alpha} + G_z N_{\delta_e\delta_T}^{\dot{h}a_z'} + G_\delta N_{\delta_T}^{\dot{h}}}{N_{\delta_e}^{\theta} + G_\alpha N_{\delta_e\delta_T}^{\theta\alpha} + G_z N_{\delta_e\delta_T}^{\theta a_z'} + G_\delta N_{\delta_T}^{\theta}} \tag{6}$$

This complex expression (each of the numerator and denominator terms are polynomials or ratios of polynomials) is the reason for the high-order numerical form of the response ratio shown in Fig. 3. But the form of the Bode plot is relatively simple and can be approximated at low frequencies by an expression of the form

$$\frac{\dot{h}}{\theta} \doteq \frac{A_h'}{A_\theta'}\frac{(1/T_{h_1}')(1/T_{h_2}')(1/T_{h_3}')}{[\zeta_{\theta_2}',\omega_{\theta_2}']} \tag{7}$$

where the primes denote that the APCS is closed. The poles and zeros are indicated in literal form in Fig. 3. The zeros

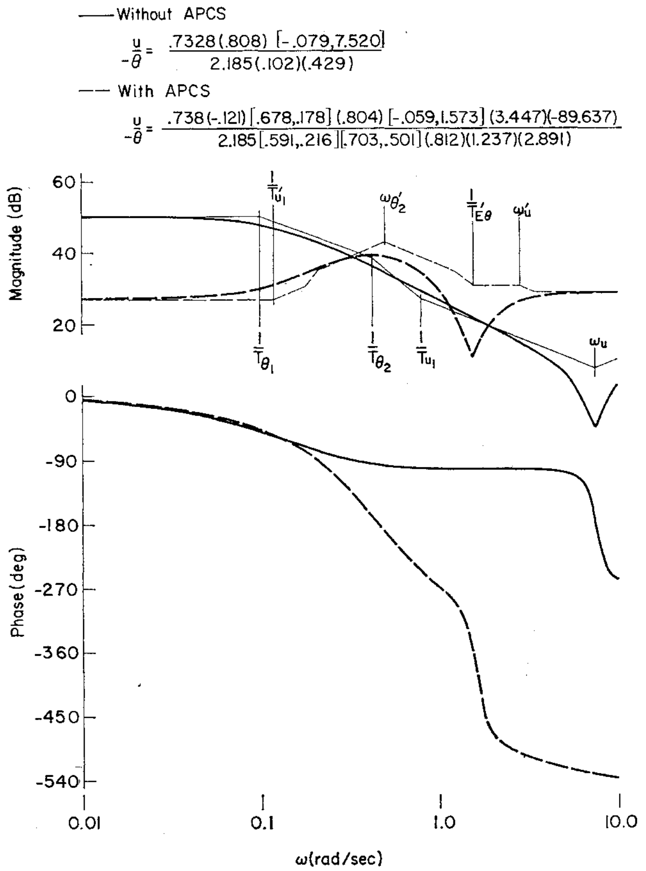

Fig. 5 Airspeed response to pitch commands.

at $1/T_{h_2}'$ and $1/T_{h_3}'$ change relatively little in this example, but the lower frequency poles and zeros change significantly. The complex pair, $[\zeta_{\theta_2}', \omega_{\theta_2}']$, replaces $(1/T_{\theta_1})(1/T_{\theta_2})$ and $1/T_{h_1}$ moves to a much higher frequency to become $1/T_{h_1}' \doteq \omega_{\theta_2}'$.

The initial γ response is slightly faster than the bare airplane's (because $1/T_{\theta_2}' \leq \omega_{\theta_2}' \leq 1/T_{h_1}'$ in this example) and settles out at the commanded attitude, rather than at some lower value (see Fig. 4); the latter because the APCS constrains the angle of attack to a single reference value (i.e., $\gamma_{ss} = \theta_c - \alpha_{\text{ref}}$). In this respect the APCS acts to make flight path response look like that of an airplane well on the "front side" of the thrust required curve (with responses characterized by ω_{θ_2}', etc., rather than $1/T_{\theta_2}$). This action is desirable and basic to the APCS function. However, any attitude change now results in an appreciable flight path change if it persists for time longer than $1/\omega_{\theta_2}'$. Attitude control must therefore be more precise; and this is sometimes difficult to accomplish manually because of APCS-induced changes in the steady-state attitude-to-elevator response.

Airspeed Responses

Changes in aircraft attitude used for flight path correction also result in airspeed changes; these changes are equally important to the carrier approach task. Figure 5 compares conventional and APCS-equipped aircraft speed responses for an attitude input. Again the low-frequency approximation to the characteristic response (valid at frequencies below the short period) can be expressed by the numerator response ratio which, for conventional (no APCS) aircraft, is given by

$$\frac{u}{\theta_c} \doteq \frac{N^u_{\delta_e}}{N^\theta_{\delta_e}} \doteq \frac{A_u(1/T_{u_1})(\zeta_u, \omega_u)}{A_\theta(1/T_{\theta_1})(1/T_{\theta_2})} \tag{8}$$

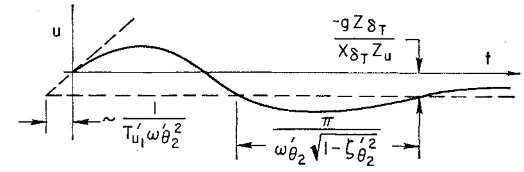

Fig. 6 Airspeed response with APCS.

In the low frequency region, the airspeed response of the APCS-equipped aircraft is approximated by

$$\frac{u}{\theta} \doteq \frac{A_u'(1/T_{u_1}')[\zeta_u', \omega_u']}{A_\theta'[\zeta_{\theta_2}', \omega_{\theta_2}'](1/T_{E\theta}')} \tag{9}$$

which can be approximated by a still simpler expression at frequencies below ω_u' and $1/T_E'$

$$\frac{u}{\theta} \doteq \frac{(-gZ_{\delta_T}/X_{\delta_T})T_{u_1}'\omega_{\theta_2}'}{Z_u} \frac{(1/T_{u_1}')}{[\zeta_{\theta_2}', \omega_{\theta_2}']} \qquad \omega \ll \omega_u', 1/T_E' \tag{10}$$

Comparing this with Eq. (8) we see that $[\zeta_{\theta_2}', \omega_{\theta_2}']$ replaces $(1/T_{\theta_1})(1/T_{\theta_2})$ as before, and (Fig. 5) $1/T_{u_1}$ moves to low frequencies and becomes a negative $1/T_{u_1}'$, such that $|1/T_{u_1}'| \doteq 1/T_{\theta_1}$. The Bode (Fig. 5) shows a radical change, with the steady-state amplitude dramatically reduced and the response peaking with considerable change in the phasing near ω_{θ_2}'. At ω_{θ_2}' the phase is approximately 180°, so that attitude maneuvers in this frequency range result in large out-of-phase speed changes, i.e., nose-up results in a speed increase. However, at low frequencies the phasing is conventional due to the non-minimum phase zero at $1/T_{u_1}'$ As discussed previously, the airspeed initially goes the wrong way, but the final value, exaggerated for clarity in Fig. 6, is in the usual direction (i.e., reduced speed for nose-up attitude). The initial airspeed excursion is actually larger relative to the final value than shown in Fig. 6.

Note that the key parameters of the response are: $-Z_{\delta_T}/X_{\delta_T}$ which is, of course, the inclination of the thrust vector with respect to the flight path, α_{TL}; $1/T_{u_1}'$, the low frequency zero in the speed response (also related to α_{TL}^1); and the attitude numerator zeros, i.e., ζ_{θ_2}' and ω_{θ_2}'.

Along with this airspeed response is an accompanying throttle (or thrust) response which will also be dominated by the mode at ω_{θ_2}'. The initial thrust surge affects the flight path response as well as airspeed to the extent that it acts as a lift augmentation (DLC) device because of large inclination (α_{TL}) and rapid thrust response. But it acts both ways—a tipover will initially result in the thrust being retarded to near idle. This is disturbing to the pilot, particularly if the engines' recovery from underspeed conditions is slow. Also, the "temporary" airspeed errors produced (for periods of time corresponding to half the period of ω_{θ_2}'—about 6 sec for the aircraft of Fig. 5) aren't temporary enough in many situations (e.g., burble transit) to avoid loss of lift.

It appears that the desired and "logical" (e.g., based on pilot comments) response is a smooth, monotonic transition between the initial and final values of airspeed and thrust. To obtain this response with a system similar to this example requires a smooth, gradual change in attitude (i.e., at frequencies below $1/T_{u_1}'$) (Fig. 5). This implies that flight path corrections must be introduced as very low-frequency inputs (i.e., $\omega \leq 0.1$ rad/sec); but these cannot then cope with the burble disturbance frequencies which approach 0.8 rad/sec. As a consequence, the pilots do accept some throttle "thrash" and "wrong way" airspeed transients in maneuvering, but to minimize this requires that ζ_{θ_2}' be large and/or ω_{θ_2}' be close to $1/T_{u_1}'$. Referring to Fig. 5, the objective is to minimize the gain difference between the peak at ω_{θ_2}' and the low frequency values; in short, to minimize the u response to δ_e.

This unfortunately can imply a relatively low value for ω_{θ_2}', since $1/T_{u_1}'$ is fundamentally quite low; therefore, this objective is in conflict with the desire for a high value of ω_{θ_2}' necessary for rapid flight path angle responses.

Current APCS design practice attempts to resolve this conflict by configuring the elevator crossfeed to allow large values of ω_{θ_2}' on pull-up, and low values on pushover. The pilot does not mind, and even desires, thrust overshoots of the final value in such pull-up situations as low and slow; but he objects strenuously to undershoots of any kind, as noted above, including those generated in pushovers. This desirable difference (in ω_{θ_2}') is obtained by using different smoothing (lag) time constants for nose-up as opposed to nose-down elevator-to-throttle inputs. In turn, this results in a rectifier-like action in the crossfeed which, as shown in Ref. 1, permits the pilot to "temporarily" regulate thrust, and consequently airspeed, by "cycling" the stick.

Governing Closed-Loop Airframe/APCS Parameters

The preceding discussions have identified the important parameters or characteristics which govern the problems encountered with the current APCS concept. We will now show briefly how the APCS functions (i.e., the feedback and feedforward terms and their respective gains and time constants) affect the governing closed-loop airframe/APCS parameters and, furthermore, show what inhibits getting the desired characteristics.

The aforementioned aspects will be demonstrated largely by the use of literal, approximate "low-frequency" factors. These expressions were derived in Ref. 1 for the closed-loop airframe/APCS and directly display the (approximate) dependence of the transfer function poles and zeros on airplane and APCS parameters. We will draw on results of Ref. 1 for the expressions given in Table 2 without additional clarification to avoid the complexities of their derivation which, while a pleasing academic exercise, adds little to the current discussions. Note that the generic form of the APCS laws (for α and n_z feedback and δ_e feedforward) used in the derivation are:

$$G_\alpha = U_0 G_w = \frac{U_0 K_w(s + 1/T_I)}{s(s + 1/T_E)}$$

$$G_z = \frac{K_z}{s + 1/T_E} \tag{11}$$

$$G_{\delta_e} = \frac{K_\delta s}{(s + 1/T_w)(s + 1/T_E)}$$

The engine-lag time constant T_E is not at the designer's disposal (e.g., lead-lagging the throttle to reduce the effective T_E results in undesirably large and objectionable throttle motion); also, the integrator inverse time constant, $1/T_I$, is small in order to preserve the desired basic α feedback properties. When used, the elevator washout inverse time constant, $1/T_w$, is also small, but larger than $1/T_I$. The Eq. (11) expressions do not include sensor dynamics since these can always be removed from the frequency region of interest by simple equalization. Again, we will consider only the flight path and corresponding speed responses to attitude inputs. The primary objective of what follows is to show the APCS parameters and airframe derivatives define the dominant (problem-causing) airframe/APCS characteristics.

Flight Path Angle Response to Attitude

The flight path angle response to attitude changes is given by (using the Table 2 expressions):

$$\left.\frac{\gamma}{\theta}\right]_{APC} = \frac{N_{\delta_e}^{\gamma''}}{N_{\delta_e}^{\theta'''}} = \frac{-Z_w(s^2 + 2\zeta_\gamma\omega_\gamma s + \omega_\gamma^2)}{(s + 1/T_E')(s^2 + 2\zeta_{\theta_2}'\omega_{\theta_2}'s + \omega_{\theta_2}'^2)} \tag{12}$$

where, defining $K \equiv K_w + K_\delta(M_w/M_{\delta_e})$, for convenience

$$\frac{\omega_\gamma^2}{\omega_{\theta_2}'^2} \doteq \frac{-X_{\delta_T}(Z_u/Z_w)K}{X_{\delta_T}Z_uT_EK - Z_w/T_w}$$

$$\doteq \frac{-X_{\delta_T}KZ_u/Z_w}{X_{\delta_T}Z_uT_EK(1 - Z_w/X_{\delta_T}Z_uKT_ET_w)} \doteq -\frac{1}{Z_wT_E} \tag{13}$$

We see therefore that ω_γ approximately "tracks" ω_{θ_2}' regardless of APCS gains, engine response, or airplane configuration. Because of this tracking and the near critical value of ζ_γ, discussed below, the basic response is largely first-order in nature with an initial break at ω_{θ_2}' which is invariably less than ω_γ according to the above relationship (i.e., Z_w is usually less than 0.5 to 0.7 and T_E is usually less than 1.0). This general behavior coincides with that given in the response diagram of Fig. 3.

Notice also from Table 2 that $2\zeta_{\theta_2}'\omega_{\theta_2}' \doteq Z_w + 1/T_w$ does not vary with APCS gain (K_w, K_δ) when the engine time constant is "large" (i.e., $T_E \doteq 1$), whereas $2\zeta_\gamma'\omega_\gamma'$ increases with increasing APCS gain (see Table 2). Thus the numerator frequency and damping both tend to increase with increasing gain so that the relative damping ζ_γ' remains roughly constant; in fact ζ_γ' is usually near critical and quite often the second-order breaks up into two first orders as indicated in Table 2 and shown in Fig. 3. The denominator damping ratio, ζ_{θ_2}', decreases for increasing gain. Accordingly, we conclude that for a slow responding engine the APCS cannot be used effectively to increase the flight path frequency ω_{θ_2}' since any increase will result in increased "peakiness" of the path response. Although the total path damping, $2\zeta_{\theta_2}'\omega_{\theta_2}'$, remains roughly constant, the reduced ζ_{θ_2}' and attendant peaked amplitude response imply excessive thrust surging and overshoot tendencies.

On the other hand, Table 2 shows that for a fast engine ($T_E \ll 1$), $2\zeta_{\theta_2}'\omega_{\theta_2}'$ is changed by the APCS gains as shown below

$$2\zeta_{\theta_2}'\omega_{\theta_2}' \doteq -Z_w - X_u + 1/T_w + T_E[K_zX_{\delta_T}Z_u + K_wZ_{\delta_T}(1 + K_\delta M_w/K_wM_{\delta_e})] \tag{14}$$

In this case, the K_z term is usually dominant since normally $X_{\delta_T} \gg Z_{\delta_T}$; accordingly, increases in the acceleration feedback gain provide an effective damping term through the interaction of the lift change with speed (i.e., Z_u) to produce a pseudo X_u term. However, it is significant that if the thrust inclination is large, the K_w gain also provides a direct improvement in Z_w akin to a DLC feedback which also increases the path damping.

Airspeed Response to Attitude

From Table 2 the airspeed response to pitch attitude is:

$$\left.\frac{u}{\theta}\right]_{APC} = \frac{N_{\delta_e}^{u'''}}{N_{\delta_e}^{\theta'''}} \doteq \frac{(X_\alpha - g)(s + 1/T_{u_1}')(s + 1/T_{u_2}')}{(s + 1/T_E')[s^2 + \zeta_{\theta_2}'\omega_{\theta_2}'s + \omega_{\theta_2}'^2]}$$

where

$$\frac{1}{T_{u_1}'} \doteq \frac{-gZ_w(1/T_E)}{U_0X_{\delta_T}(K_w + K_zZ_w + K_\delta M_w/M_\delta)} + \frac{g}{U_0}\frac{Z_{\delta_T}}{X_{\delta_T}} \tag{15}$$

All the airplane parameters in the expression for $1/T_{u_1}'$ are normally negative except $1/T_E$ and X_{δ_T}; and the result is that both terms contributing to the value of $1/T_{u_1}'$ are negative. Therefore, $1/T_{u_1}'$ is invariably nonminimum phase, and as the APCS gain is increased its absolute value (always small) decreases. Thus increasing the APCS gains (e.g., K_w and K_δ) increases the value of ω_{θ_2}' (noted above) and decreases $1/T_{u_1}'$, and thereby increases their relative separation. Increasing the separation between ω_{θ_2}' and $1/T_{u_1}'$ increases both the magnitude of the initial u response transient and the time required to return to the steady-state value, with associated effects in the thrust, α, etc., responses. Therefore, this

Table 2 Summary of pertinent low frequency airplane plus APCS approximate factors

FACTORED FORMS	APPROXIMATE FACTORS
$\Delta'' \doteq \dfrac{-M_\alpha\left(s+\frac{1}{T_I''}\right)\left(s^2+2\zeta_p''\omega_p''s+\omega_p''^2\right)\left(s+\frac{1}{T_{E,Z_u}'}\right)}{s\left(s+\frac{1}{T_E}\right)}$	$\omega_p''^2 \doteq -\frac{g}{U_o} Z_u \frac{T_{E,Z_u}'}{T_E}$; $2\zeta_p''\omega_p'' \doteq -X_u \frac{T_E'}{T_E''}$ $\frac{1}{T_E''} \doteq \frac{1}{T_E} + \frac{g}{U_o}\frac{Z_u}{X_u} + \frac{\delta_T}{X_u M_w}(K_w M_u - K_z Z_u M_w)$ $\frac{1}{T_{E,Z_u}'} \doteq \frac{1}{T_E'} + X_u \frac{T_E'}{T_E''} \doteq \frac{1}{T_E'}$ $\frac{1}{T_E'} \doteq \frac{1}{T_E} - X_u + K_z Z_{\delta_T} \doteq \frac{1}{T_E}$ $\frac{1}{T_I''} = \frac{1}{T_{Z_u}''} \doteq \frac{g}{U_o}\frac{Z_u}{X_u}\frac{T_E''}{T_E}$ $\frac{1}{T_I'} + \frac{1}{T_w'} \doteq \frac{1}{1+\frac{K_\delta M_w}{K_w M_{\delta_e}}}\left(\frac{1}{T_I}+\frac{1}{T_w}\right)$; $\frac{1}{T_I' T_w'} \doteq \frac{1}{1+\frac{K_\delta M_w}{K_w M_{\delta_e}}}\left(\frac{1}{T_I T_w}\right)$
$N_{\delta_e}^{\theta'''} \doteq \dfrac{M_{\delta_e}\left(s+\frac{1}{T_I'}\right)\left(s+\frac{1}{T_w'}\right)\left(s+\frac{1}{T_E'}\right)\left(s^2+2\zeta_{\theta_2}'\omega_{\theta_2}'s+\omega_{\theta_2}'^2\right)}{s\left(s+\frac{1}{T_w}\right)\left(s+\frac{1}{T_E}\right)}$	$\omega_{\theta_2}'^2 \doteq -X_{\delta_T} Z_u\left(K_w + K_\delta \frac{M_w}{M_{\delta_e}}\right)T_E - \frac{Z_w}{T_w}$ $2\zeta_{\theta_2}'\omega_{\theta_2}' \doteq -Z_w + \frac{1}{T_w}$; "large" T_E (≥ 1) or $2\zeta_{\theta_2}'\omega_{\theta_2}' \doteq -Z_w - X_u + \frac{1}{T_w} + T_E\left[K_z Z_u X_{\delta_T} + K_w Z_{\delta_T}\left(1+\frac{K_\delta M_w}{K_w M_\delta}\right)\right]$; "small" T_E ($\ll 1$) $\frac{1}{T_E'} \doteq \frac{1}{T_E} - X_u + K_z Z_\delta \doteq \frac{1}{T_E}$
$\left(s+\frac{1}{T_{h_1}'}\right)\left(s+\frac{1}{T_{h_2}'}\right)$ or $N_{\delta_e}^{\gamma''} \doteq \dfrac{-M_{\delta_e} Z_w\left(s+\frac{1}{T_I'}\right)\left(s+\frac{1}{T_w'}\right)\left(s^2+2\zeta_\gamma\omega_\gamma s+\omega_\gamma^2\right)}{s\left(s+\frac{1}{T_w}\right)\left(s+\frac{1}{T_E}\right)}$	$\omega_\gamma^2 \doteq -X_{\delta_T}\frac{Z_u}{Z_w}\left(K_w + K_\delta \frac{M_w}{M_{\delta_e}}\right)$ $2\zeta_\gamma\omega_\gamma \doteq \frac{-Z_{\delta_T}}{Z_w}\left(K_w + K_\delta \frac{M_w}{M_{\delta_e}}\right) + \frac{1}{T_E}$
$N_{\delta_e}^{u'''} \doteq \dfrac{M_{\delta_e}(X_\alpha - g)\left(s+\frac{1}{T_I'}\right)\left(s+\frac{1}{T_w'}\right)\left(s+\frac{1}{T_{u_1}'}\right)\left(s+\frac{1}{T_{u_2}'}\right)}{s\left(s+\frac{1}{T_w}\right)\left(s+\frac{1}{T_E}\right)}$	$\frac{1}{T_{u_1}'} \doteq \dfrac{-gZ_w \frac{1}{T_E}}{X_{\delta_T}\left(K_z Z_\alpha + K_\alpha + K_\delta \frac{M_\alpha}{M_{\delta_e}}\right)} + \frac{g}{U_o}\frac{Z_{\delta_T}}{X_{\delta_T}}$ $\frac{1}{T_{u_2}'} \doteq \frac{1}{T_E} + \dfrac{gZ_w - X_{\delta_T}\left(K_z Z_\alpha + K_\alpha + K_\delta \frac{M_\alpha}{M_{\delta_e}}\right)}{(X_\alpha - g)}$

represents a conflict with path control desires which center on large values of ω_{θ_2}' as discussed previously. Another conflict is present in that $1/T_{u_1}'$ responds to changes in K_z whereas ω_{θ_2}' does not. Accordingly, this represents a second tradeoff area between the values of K_z and K_w: the first, as noted, being the K_z, K_w consideration (for "small" T_E) entering into the "desired" values of ζ_{θ_2}', ω_{θ_2}'.

The implication of the above is that effective tradeoff possibilities (in the relative values assigned to K_z and K_w) to achieve good path mode damping and response (remember that ω_{θ_2}' depends mostly on K_w) depend on the basic airframe characteristics and in particular on the engine lag. For slow engine response (which implies constant $\zeta_{\theta_2}'\omega_{\theta_2}'$ regardless of APCS gains), the APCS is directly responsible for the lightly damped path mode and associated piloting difficulties encountered during ACLS operation (i.e., ACLS with manual takeover at 200 ft). Conversely, with a fast engine response, the APCS can be used effectively to improve the path damping.

Summary and Conclusions

The foregoing discussion of the altitude rate and airspeed responses of the aircraft equipped with an APCS of the current concept (Fig. 1) correlates various response parameters with most of the problems listed in Table 1. In so doing, the nature of some of the compromises inherent in the APCS design is indicated. One example of central importance is the attitude numerator factor ω_{θ_2}', which has as much importance as $1/T_{\theta_2}$ for conventional aircraft. The designer can choose large values for this parameter to improve the altitude response and thus the ability of the aircraft to follow commands and suppress disturbances. In doing this, he also chooses thrust and airspeed surges (because ω_{θ_2}' is separated from $1/T_{u_1}'$) and increased sensitivity of attitude (hence flight path angle) to elevator position. In current designs, intentional nonlinearities are introduced which give large effective ω_{θ_2}' for nose-up attitude changes, and small ω_{θ_2}' for nose-down changes. This asymmetry also provides some measure of auxiliary thrust control (by means of cycling the stick) which is otherwise lacking. This in turn restores some of the flexibility lost when going to a single point controller (elevator) for flight path.

The key parameters which, in an over all sense, govern the APCS-airframe compatibility are: basic airframe heave damping, Z_w, engine response time constant, T_E, effective airframe-engine configuration, i.e., thrust inclination, $Z_{\delta T}/X_{\delta T}$.

From a design viewpoint we find that the important parameters of the aircraft responses depend on the same APCS gains. Thus, as in the case of flight path control, it is difficult to improve the characteristics without degrading the related responses (e.g., airspeed and engine surging for flight path control). Consequently, the final APCS configurations (i.e., gains and equalization) must represent a compromise. The more specific observations reviewed briefly below point up the major factors involved and the nature of the compromises required.

The change in flight path response, which is governed by the parameter ω_{θ_2}', is defined primarily by the angle of attack feedback gain, K_w. This is consistent with one (sometimes not fully appreciated) role of the broadband angle of attack feedback, i.e., holding $\alpha \doteq$ const, to make $\gamma/\theta \to 1$, and thereby to improve flight path response. Further consideration of this role leads to the need for path damping which in the present concept is provided primarily by the normal acceleration feedback, K_z. Unfortunately, the degree of path damping which may be introduced with the APCS is limited by the engine response lag, T_E. In fact, for slow engines the basic aircraft heave damping term Z_w tends to set the total path damping, $\zeta_{\theta_2}'\omega_{\theta_2}'$, regardless of APCS gains. For reasonably fast engines which do not limit the attainable values of $\zeta_{\theta_2}'\omega_{\theta_2}'$, there is an implicit trade to be made (K_z vs K_w) between improved flight path response and path damping which also reflects on the level of engine or throttle activity.

Airspeed responses associated with commands (i.e., attitude inputs, in particular for flight path control) and disturbances infer additional considerations and compromises. Improved flight path response is achieved primarily through transient airspeed changes ensuing from the APCS's thrust commands which attempt to constrain or prevent angle-of-attack changes regardless of source (i.e., command input or gust disturbance). The primary factor affecting airspeed and associated throttle surges in response to attitude commands is the relative displacement between ω_{θ_2}' and the speed indexing term, $1/T_{u_1}'$. The frequency spread between these two terms, in combination with the effective damping or settling time of angle-of-attack excursions $\zeta_{\theta_2}'\omega_{\theta_2}'$, is responsible for the often erratic and unacceptable throttle behavior which is a recurring criticism.

In summary, the results show that the APCS acts to modify not only the airspeed, but also the flight path angle responses to pitch attitude changes. In so doing, the handling qualities of the aircraft are changed significantly in the low and intermediate frequency regions, and not always beneficially, thus creating certain problems in APCS design. Successful resolution of these problems requires recognition of all the roles played by the Approach Power Compensator System at the outset of the APCS design process.

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