Proposal and Flight Evaluation of a New Pitch-Mode Decoupling System

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A new pitch-mode decoupling system is proposed and evaluated by flight tests using an experimental airplane. In the proposed system, both speed stability and static stability are nullified by feedback of air speed and angle-of-attack variations into the elevator. Pitch stability is augmented through feedback of pitch attitude and its time rate into the elevator. The resulting system attains the same goal as the infinitely high gain θ-closure system, while requiring only a finite servo bandwidth. After pitch-loop closure, there remains an inherent control cross coupling, where air speed and flight-path angle responses to thrust input are unfavorably modified and thus produce possible speed excursions. A simple crossfeed of throttle command into attitude command solves the problem. Flight test results are included.

Nomenclature

$C_L, C_{L\alpha}$	= lift coefficient and lift curve slope
d	= glide slope deviation
g	= gravitational acceleration
K	= feedback gains with appropriate subscripts
$N(s)$	= numerator polynomial with appropriate super/subscripts
q	= pitch rate
R_t	= control crossfeed gain ratio
s	= argument of Laplace transform
T	= time constant with appropriate subscripts
U_0	= trim speed
u_a, w_a	= air speed components along stability axis
u_g, w_g	= gust components along stability axis
α	= angle of attack
γ	= flight-path angle in inertial space
$\Delta(s)$	= characteristic polynomial
Δ_e, Δ_t	= column/throttle input
δ_e	= elevator deflection
ζ	= damping ratio
θ, θ_{cmd}	= pitch attitude, pitch attitude command
τ	= thrust variation/weight ratio
ϕ_e, ϕ_t	= angle of steady-state vectors due to column and throttle input, respectively
ω	= frequency

Superscripts

$'$	= control crossfeed
$*$	= control crossfeed with ϕ_t = 90 deg

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Introduction

AMONG various control strategies, tight pitch-attitude controls are often discussed in connection with the pilot's manual control, as well as in constructing basic flight-control systems. In either case, pitch-attitude control is not the final objective in itself but is taken as an inner control loop for other outer-loop tasks. Specifically, it has been said that precise pitch-attitude control is to be used as a command reference for path and speed control.[1] As to manual control, it has been reported recently that the tightness of the pilot's pitch-attitude closure is limited in frequency range and is accompanied by a large phase lag in the closed-loop frequency response function, and therefore, that caution should be exercised in making the assumption of high-gain pitch-attitude closure.[2] This implies the difficulties associated with manual pitch-attitude control under some outer-loop tasks and seems to support the statement that most pilot ratings appear to be primarily determined by how precisely the pilot can control the airplane's pitch attitude.[3] Tightness of automatic pitch control is specified by its bandwidth. The bandwidth is specified by pitch feedback gain, and a high-gain pitch closure (HGPC) system is a natural consequence.

The other motive for HGPC originates in relaxed static stability (RSS) requirements where the derivative M_α gives insufficient stability by definition. There remains little reason, even if it were possible, to rely on speed stability M_u for keeping inherent stabilities. A variety of feedback structures for augmentation are summarized in Ref. 4. Again, HGPC seems to be a most promising candidate system. The term "superaugmented" is defined[4] as a system applicable to aircraft that 1) are statically unstable without augmentation; 2) have a degree of pitch-attitude stability with respect to inertial space; and 3) have pilot command/aircraft pitch-response characteristics that are largely independent of the aerodynamic stability derivatives. For such aircraft, HGPC effectively cancels short period divergence and subsidence with zeros of (pitch attitude)/(elevator) transfer function. The resulting pitch-attitude response to pitch-attitude command is specified by modified phugoid poles and an assigned zero.[4,5]

In an HGPC system, pitch mode is stabilized against gust disturbances only to the extent of the modified closed-loop poles. In fact, a finite pitch feedback gain leaves finite gust excitations in the pitch mode. Only infinitely high gain pitch closure (IHGPC) perfectly stabilizes pitch motion from gust excitation. In a sense, decoupling of pitch mode is perfect with IHGPC and is approximate with HGPC. If precise pitch-attitude control is of essential value in aircraft control, IHGPC should work better than HGPC.

In this paper, first we propose a new pitch mode decoupling system,[6] which is named "relaxed speed and static stability (RSS^2)" because both speed and static stability M_u and M_w are intentionally nullified by appropriate feedback of air data. The goal is the same as that of the IHGPC while requiring only reasonably low bandwidth to elevator servos.

Pitch-mode decoupling leaves a slow mode comprising speed and flight-path variations. Control of the slow mode using both elevator and thrust is reduced to a two-input/two-output manual control problem. The control characteristics have been investigated extensively from the standpoint of handling qualities in connection with powered lift aircraft.[1] Also, it is said that a pilot is not likely to regulate air speed tightly, or the air-speed regulation is at a lower bandwidth.[7] This situation is somewhat discouraging, especially when expenditures have been made to reduce every kilometer per hour in approach speed, as with short takeoff and landing aircraft. In addition to the sluggish air-speed response, two other properties seem to be inherent to pitch-mode decoupling. These are 1) unfavorable thrust-control coupling into air speed and flight path and 2) increased u_a/u_g response at the low-frequency range, both of which give rise to speed excursions and make the pilot's speed-control task more demanding.

As the second stage, we propose a simple control crossfeed from throttle into attitude. The crossfeed system was devised to avoid the difficulties associated with thrust-control cross coupling and the tendency to speed excursions.

A flight-test program has been conducted for evaluating the proposed pitch-mode decoupling with attitude command and the throttle-control crossfeed into attitude, and for determining their flying quality attributes in a glide-slope tracking task. The pitch-mode decoupling system was devised during development of an in-flight simulator mainly to cope with the problem of limited servo bandwidth. The in-flight simulator is named "Variable Stability and Response Airplane (VSRA)"[8] and is an implementation of an explicit model-following system[9] comprising both feedback and feed-forward loops. Flight-test results included in the paper were, however, obtained with only the feedback loop engaged. Flight-test results are shown to support pertinent discussions.

RSS^2 System

Temporarily assuming sufficiently high bandwidth response to elevator and throttle, the longitudinal equation of motion referred to stability axis is given by[7]

$$\begin{bmatrix} \dot{u}_a \\ \dot{\gamma} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} X_u & -X_\alpha & 0 & X_\alpha - g \\ -Z_u/U_0 & Z_w & 0 & -Z_w \\ M_u & -M_\alpha & M_q & M_\alpha \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} u_a \\ \gamma \\ q \\ \theta \end{bmatrix}$$

$$+ \begin{bmatrix} X_\tau & 0 \\ -Z_\tau/U_0 & 0 \\ M_\tau & M_{\delta e} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \tau \\ \delta_e \end{bmatrix} + \begin{bmatrix} -1 & -X_w \\ 0 & Z_w/U_0 \\ 0 & -M_w \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{u}_g \\ w_g \end{bmatrix} \tag{1}$$

where notations for derivatives are standard, and missing derivatives are assumed to be zero. In Eq. (1), state variables u_a and γ are used because they are considered to be of primary importance in an approach flight phase, and a point approximation for gust representation[11] is used wherein spacewise variations over aircraft size are ignored in frozen gust.

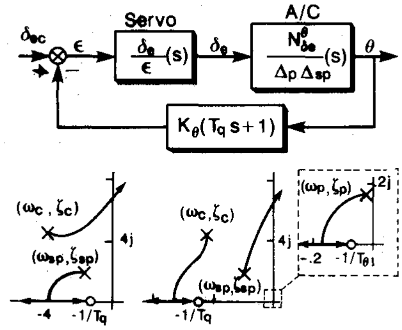


Fig. 1 Typical root loci of HGPC; left: large T_q, right: small T_q.

HGPC Control Law

An HGPC control law

$$\delta_e = -K_\theta(T_q q + \theta) + K_e \Delta_e \tag{2}$$

defines the closed-loop characteristics. The gains (K_θ, T_q) are chosen primarily to satisfy the bandwidth requirement for pitch command. Typical root loci including servo dynamics are shown in Fig. 1. Assume that a desirable bandwidth ω_θ and stability ζ_θ have been obtained. Gust response characteristics are modified by HGPC. Since the numerator polynomials of transfer functions (θ/u_g) and (θ/w_g) are invariant to the loop closure, the pitch-mode gust response is alleviated in comparison with the unaugmented configuration only to the extent that the closed-loop poles are stabilized. In this sense, pitch mode is only approximately decoupled with HGPC. Pitch mode can be decoupled perfectly, or become free from gust disturbances, only with IHGPC. Figure 1 also elucidates how the root loci of conventional aircraft such as VSRA tend to become unstable with higher gains when a low bandwidth servo is used. For a second-order servo, appropriate lead/lag compensation in pitch feedback may increase stability margin in a particular frequency band. However, using a compensator of a proper transfer function, the loop transfer function has an excess number of poles over the number of zeros, which must be at least two, and the total system damping remains unaltered[10] after loop closure. With higher gains, lack of total system damping necessarily causes an instability in some other frequency band, such as that corresponding to elastic modes. Being motivated by the desire for a system equivalent to the IHGPC but that uses only moderate feedback gains, the RSS^2 system was devised.

RSS^2 Control Law

Instead of Eq. (2), the RSS^2 control law requires

$$\delta_e = -(K_{u_a} u_a + K_{w_a} w_a + K_\tau \tau) - K_\theta(T_q q + \theta) + K_e \Delta_e \tag{3}$$

where K_θ and T_q are chosen for arbitrarily specified $(\omega_\theta, \zeta_\theta)$,

$$K_\theta = \omega_\theta^2 / M_{\delta e}, \qquad K_\theta T_q = (M_q + 2\zeta_\theta \omega_\theta)/M_{\delta e} \tag{4a}$$

Assuming that the spectra of resultant u_a, w_a, and τ are of reasonably lower frequency contents than the elevator servo bandwidth, gains are chosen to satisfy the following condition:

$$(K_{u_a}, K_{w_a}, K_\tau) = (M_u, M_w, M_\tau)/M_{\delta e} \tag{4b}$$

Referring to Eq. (1), the longitudinal equation of motion is residualized,[12] and a fast mode, that is, the pitch mode, is given by

$$\begin{bmatrix} \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -2\zeta_\theta \omega_\theta & -\omega_\theta^2 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} q \\ \theta \end{bmatrix} + \begin{bmatrix} K_e M_{\delta e} \\ 0 \end{bmatrix} \Delta_e \tag{5a}$$

and a slow mode, which comprises air-speed and flight-path variations, is given by

$$\begin{bmatrix} \dot{u}_a \\ \dot{\gamma} \end{bmatrix} = \begin{bmatrix} X_u & -X_\alpha \\ -Z_u/U_0 & Z_w \end{bmatrix} \begin{bmatrix} u_a \\ \gamma \end{bmatrix} + \begin{bmatrix} X_\alpha - g & X_\tau \\ -Z_w & -Z_\tau/U_0 \end{bmatrix} \begin{bmatrix} \theta \\ \tau \end{bmatrix} + \begin{bmatrix} -1 & -X_w \\ 0 & Z_w/U_0 \end{bmatrix} \begin{bmatrix} \dot{u}_g \\ w_g \end{bmatrix} \tag{5b}$$

Fast Mode of RSS²

Equation (5a) gives the pitch-attitude response to column input, the transfer function of which is given by

$$\theta/\Delta_e = M_{\delta e} K_e / (s^2 + 2\zeta_\theta \omega_\theta s + \omega_\theta^2) \tag{6}$$

Properties of RSS² are discussed as follows.

1) The original target of perfect pitch-mode decoupling is accomplished not by brute force (IHGPC) but by nullifying the existing moment derivatives M_u, M_w, and M_τ. By the moment nullifications, Eq. (5a) or Eq. (6) indicates that the pitch dynamics of RSS² are, as with IHGPC, completely free from aerodynamic effects except for $M_{\delta e}$. They are made free from gust disturbances not by denominator modification but by nullification of the numerators of θ/u_g and θ/w_g. Actually, because of the limited bandwidth of the servo, u_g and w_g slightly excite the pitch mode. Figure 2 compares gains of $(u_a,\gamma,\theta)/(u_g,w_g)$ for the unaugmented configuration [Eq. (1)], for the HGPC [Eqs. (1) and (2) plus servo dynamics], and for the RSS² [Eqs. (1), (3), (4a), and (4b) plus servo dynamics]. In Eq. (4a), $\omega_\theta = 3$ (rad/s) and $\zeta_\theta = 0.7$ are assigned, and in Eq. (2), the same K_θ and T_q are used as those in Eq. (4a). Servo dynamics are of $\omega_c = 6.3$ rad/s and $\zeta_c = 0.7$. In Fig. 2, an almost zero response in with RSS² is obvious for $\omega < \omega_\theta$. Higher gust responses in θ with HGPC are due to imperfect decoupling of pitch dynamics. As a result of pitch stabilization with respect to the inertial space, increased response in low frequency u_a/u_g is seen in both RSS² and HGPC.

2) The feedback gains K_θ and T_q in Eq. (4b) are solely assigned from the requirement for necessary bandwidth ω_θ and damping ζ_θ of the augmented pitch mode. Since the gains are independent of the requirement for decoupling the pitch mode from others, they are of moderate magnitude and one can design the system without being annoyed by possible coupling with other dynamic modes even when elevator servos are band limited.

3) Speaking of aircraft pitch control with the RSS² system engaged, the pilot's work load is expected to be reduced because a flat-pitch response to column input up to the assigned bandwidth does not require any pilot lead, and because he does not have to regulate gust disturbances.

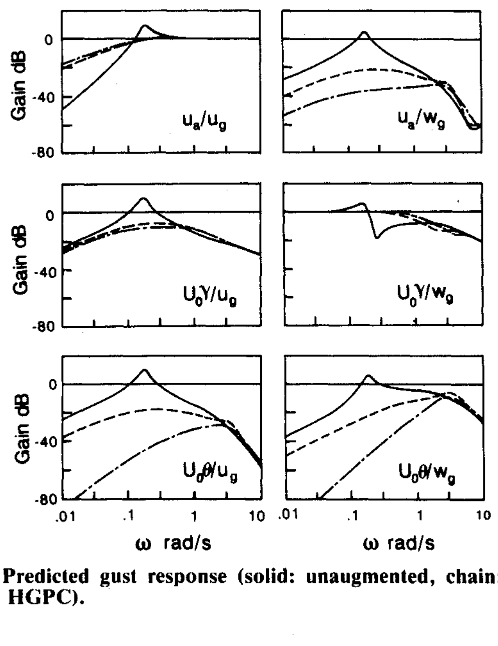


Fig. 2 Predicted gust response (solid: unaugmented, chain: RSS², broken: HGPC).

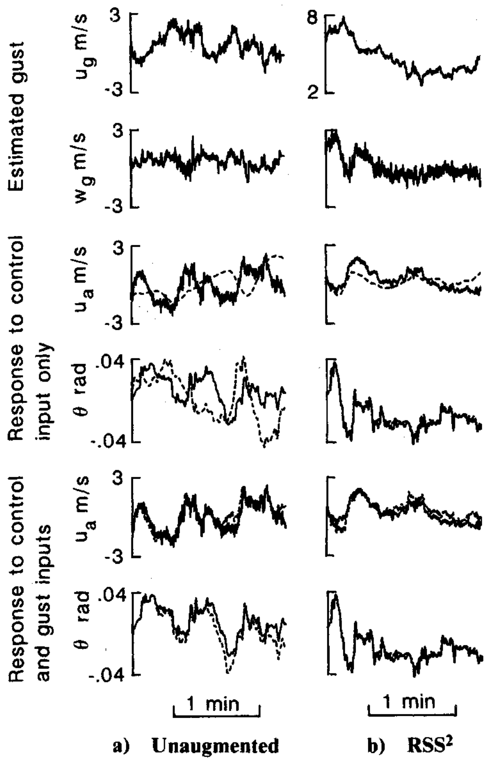


Fig. 3 Gust response verification by state reconstruction (solid: measured, broken: reconstructed).

Preliminary Flight-Test Results

Flight-test results for verifying the properties of the RSS² system are summarized as follows.

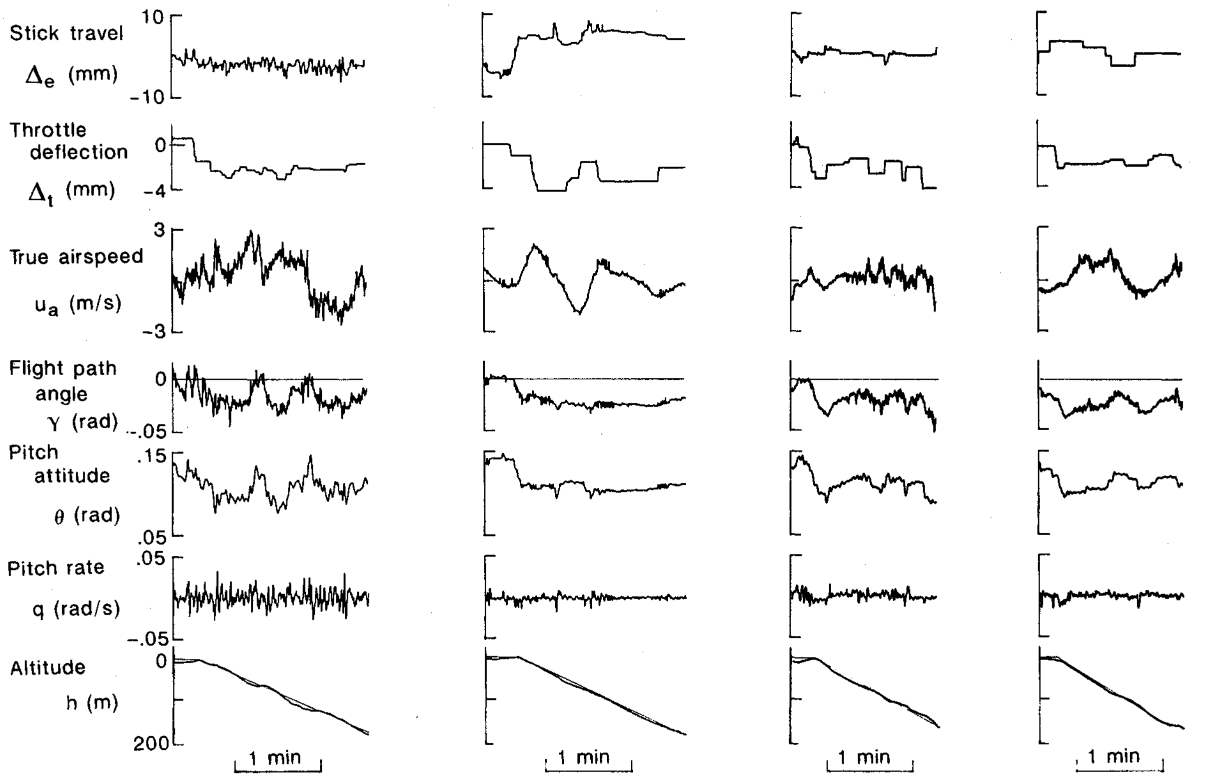
Gust Response in Pitch Mode

In Fig. 3, the estimated gust components for typical flight cases in unaugmented and RSS² configurations are compared. In estimating gust components, inertial speeds of aircraft are obtained from the appropriate Kalman filters and smoothers[13] to which Doppler radar, pressure altitude, accelerations, and attitude data are supplied.[8] The obtained gust components are checked for their validity by the state reconstruction method.[14] In the figure, the computed responses to the applied control input, u_a and θ, are compared with measured data. For the RSS², computed θ to the control input only coincides with the measured data precisely enough. On the other hand, considerable reconstruction error is seen in u_a. This error is corrected if the computed response to the estimated gust is added. For the unaugmented configuration, gust response corrections in addition to responses to the applied control are mandatory for both u_a and θ to get acceptable data reconstruction. Those reconstructions prove that the pitch mode is almost free of gust excitation when RSS² is engaged.

Glide Slope Tracking

Figures 4a and 4b compare flight-test results for glide-slope tracking of the unaugmented configuration of VSRA with those of the RSS²-based attitude command/attitude hold configuration. Again, $\omega_\theta = 3$ rad/s, $\zeta_\theta = 0.7$ was assigned. The evaluating pilot was asked to keep a minimum localizer deviation and capture a glide slope to make an instrument approach while keeping air speed as constant as possible, and then to level off.

In the RSS² configuration, as compared with the unaugmented, suppressions of pitch-rate and high-frequency column



a) **Unaugmented** b) **RSS² ($\phi_t = 18$ deg), fixed-wing pilot** c) **RSS² + crossfeed ($\phi_t = 90$ deg), fixed-wing pilot** d) **RSS² + crossfeed ($\phi_t = 90$ deg), helicopter pilot**

Fig. 4 Effects of RSS² and control crossfeed in glide-slope tracking.

movement are obvious, which implies that both gust response in pitch mode and pilot's remnant are greatly reduced.

Slow Mode of RSS²

The residualized slow mode is a point mass representation of aircraft motion comprising air speed and flight-path angle as state variables and pitch attitude θ, and thrust variation τ as control commands. It is well known[1] that the characteristic roots of Eq. (5b) are open-loop zeros of pitch/elevator transfer function, i.e., $s = -1/T_{\theta 1}$ and $s = -1/T_{\theta 2}$, which are determined by purely aerodynamic force derivatives X_u, X_w, Z_u, and Z_w. The pole $-1/T_{\theta 1} \approx X_u - (Z_u/Z_w)X_w$ is located close to the origin of the complex frequency plane and governs the speed mode, whereas the pole $-1/T_{\theta 2} \approx Z_w$ usually governs the heave mode. Again, it will be clear that the RSS² gives the same residualization as that by IHGPC.

Since the control law given by Eq. (3) comprises feedback loop into elevator, transfer-function numerators relating to column input are invariant to the loop closure. Gust response numerators are affected and have been discussed in connection with Fig. 2. Also, the numerators relative to thrust are significantly affected by the elevator loop closure.

Each entry of the transfer-function matrix $(u_a, U_0\gamma)^T/(\theta,\tau)$ of Eq. (5b) has the form $N_m^l(s)/\Delta(s) = A_{lm}(s + 1/T_{lm})/\Delta(s)$, where $l = u_a$ or $U_0\gamma$, $m = \theta$ or τ, and where $\Delta(s) = (s + 1/T_{\theta 1})(s + 1/T_{\theta 2})$. Approximated forms of gains A_{lm} and time constants T_{lm} are studied in Ref. 1 for powered-lift applications. Table 1 summarizes those for conventional aircraft such as the VSRA. Numerator zeros $s = -1/T_{u\theta} = Z_w\ [-g/(X_\alpha - g)]$ and $s = -1/T_{u\tau} = Z_w$ approximately cancel the heave mode $s = -1/T_{\theta 2}$ and thus leave $s = -1/T_{\theta 1}$ as the speed mode. Without power effect, i.e., $Z_\tau = 0$, transfer function $U_0\gamma/\tau$ has no numerator zero, and the bandwidth is essentially limited by $1/T_{\theta 1}$. This contrasts with the response of $U_0\gamma/\theta$ where $1/T_{\theta 2}$ specifies its bandwidth. For front-side operation, numerator zero $-1/T_{\gamma\theta} = X_u - (X_\alpha - g)Z_u/Z_\alpha$ is negative and for back-side operation, positive.

Table 1 Conventional[a] aircraft transfer functions to control input with RSS²

Input	u_a Response	$U_0\gamma$ Response
θ	$\dfrac{-g}{(s+1/T_{\theta 1})}$; $\dfrac{1}{T_{u\theta}} \doteq \dfrac{1}{T_{\theta 2}}$	$\dfrac{-Z_\alpha(s+1/T_{\gamma\theta})}{(s+1/T_{\theta 1})(s+1/T_{\theta 2})}$
τ	$\dfrac{X_\tau}{(s+1/T_{\theta 1})}$; $\dfrac{1}{T_{u\tau}} \doteq \dfrac{1}{T_{\theta 2}}$	$\dfrac{-Z_u X_\tau}{(s+1/T_{\theta 1})(s+1/T_{\theta 2})}$

[a]"Conventional" means $|Z_\tau| \ll X_\tau$.

Control Cross Coupling

The response characteristics of the slow mode are better understood by studying the state plane diagram of Fig. 5, where the step responses of u_a and $U_0\gamma$ to column and throttle inputs of the unaugmented air frame are compared with those with the RSS² system engaged. In the figure, each small dot indicates a 1-s interval, and the magnitude of step inputs Δ_e and Δ_t is so normalized that at the steady state $v_{ss}^2 = (u_a)^2 + (U_0\gamma)^2 = 1$ (m/s)². Besides the trajectories of the step response in the $u_a - U_0\gamma$ plane, it is more important to notice their terminal states. Vectors pointing the steady states in the $u_a - U_0\gamma$ plane for each configuration indicate nonzero set points, or retrimmable states, reached by step inputs in θ and τ, respectively. Let the angle of steady-state vectors measured from the positive u_a axis be denoted by ϕ_e (step Δ_e input) and ϕ_t (step Δ_t input), respectively. If these two steady vectors align with each other ($\phi_t - \phi_e = 0$ or $= 180$ deg), one cannot retrim the aircraft to an arbitrary $(u_a, U_0\gamma)$ point but can retrim only to a point along these vectors. In another interpre-

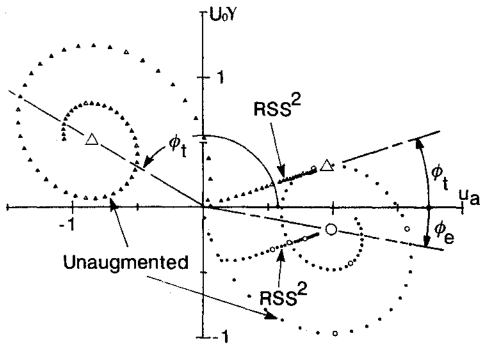


Fig. 5 Computed step responses in $u_a - U_0\gamma$ plane.

tation, near alignment of two steady-state vectors implies a strong "control cross coupling" at the frequency range below $1/T_{\theta 1}$; i.e., pilots have to use both controls in coordination to regulate two outputs at the same time. It is easy to show that

$$\tan(\phi_e) = -(U_0/g)(1/T_{\gamma\theta}) \quad (7)$$

Equation (7) indicates that $|\phi_e|$ is small in operations at around the bottom of the required power curve, which is where most aircraft are operated during a final approach.

With the RSS² system engaged, pitch attitude is held constant even when thrust is increased, and hence at steady state, flight-path angle changes as much as the change in angle of attack. On the other hand, the effect of thrust increase is shared by changes in angle of attack and in air speed. This share at the steady state is determined by purely aerodynamic relations. From Eq. (5b),

$$\begin{bmatrix} X_u & -X_w \\ -Z_u & Z_w \end{bmatrix}\begin{bmatrix} u_a \\ U_0\gamma \end{bmatrix} + \begin{bmatrix} X_\tau \\ -Z_\tau \end{bmatrix}\tau = 0 \quad (8)$$

Thus for conventional aircraft where $|Z_\tau| \ll X_\tau$, RSS² leads to a condition where

$$\tan(\phi_t) = (U_0\gamma/u_a)_{ss} = Z_u/Z_w = 2C_L/C_{L\alpha}; \quad (u_a/\tau)_{ss} > 0 \quad (9)$$

Since, for a conventional aircraft in its unaugmented configuration, $\tan(\phi_t)$ is approximately proportional to the ratio X_τ/M_τ and is usually large in its absolute value, ϕ_t scatters around 90 deg. Equation (9) gives a rough idea of how drastically the direction of steady-state responses to thrust input is modified when either RSS² or HGPC is engaged. As is the case with the VSRA, most pitch-augmented conventional take off and landing aircraft have ϕ_t that is given by Eq. (9), which is usually of a positive and small value (less than 20 deg). Therefore, not infrequently an undesirable condition arises where ϕ_t and ϕ_e almost come into alignment. In this sense, both the RSS² and HGPC systems inherently possess a potential drawback.

Front-Side Control Technique

Inspection of time histories in Fig. 4b clearly reveals the following.

1) The pilot uses attitude command for flight-path control (front-side control technique), and an acceptable level of glide-slope tracking performance is attained. This is reasonable because the VSRA is operated in the front-side of the power curve ($\phi_e = -10$ deg). If we refer to the transfer function $(U_0\gamma/\theta)$ e in Table 1 and assume pilot proportional feedback of glide-slope error d ($\dot{d} = U_0\gamma$) into pitch command θ_c, a loop transfer function d/θ_c is understood to have three poles, 0, $-1/T_{\theta 1}$, and $-1/T_{\theta 2}$, and a zero $-1/T_{\gamma\theta}$. One can imagine that a sufficient bandwidth is attainable in the closed-loop d/d_{cmd} with moderate gain. It must be noted that no pilot lead is required in the loop closure because sufficient inner-loop stability has been assured by the RSS².

2) Stepwise attitude command input at glide-slope capture gives rise to air-speed excursion in Fig. 4b. This results from the control cross-coupling effect of attitude command into air speed. The pilot has to adjust throttle command for air-speed regulation thereafter and succeeds after several readjustments, which take a long time. Since sufficient gain is available at the low frequencies of (u_a/τ) response (see Table 1), some tight loop closure by the pilot could have afforded a wider closed-loop bandwidth. Actually the method of thrust adjustment is never continuous nor linear, but intermittent, so that discrete throttle movements are applied, and the pilot waits to see what happens thereafter in air speed. This control strategy may be suitably called a class of "supervisory control"[15] where the pilot's efforts for deciding the timing of sampling and decision making of control action are included. The issues are that the required bandwidth for control may be lowered, and the task may not be easier. Within each control segment, thrust level is maintained constant piecewise, and air-speed response can be described by the open-loop characteristics. This sort of control strategy explains the statement that air-speed regulation by the pilot is at the lower bandwidth.[7] If this is an inherency of pilots, then speed excursions in the approach phase are unavoidable, as long as one sticks to the front-side control technique.

Back-Side Control Technique

In front-side operation of RSS² or HGPC aircraft, the back-side control technique may be applicable as an alternate for controlling the slow mode. For a back-side operation, the back-side control technique becomes mandatory unless autothrottle is incorporated to augment the inherent X_u derivatives and to recover front-side operations. Let us avoid this option and remain with the basic RSS² system. Since $(U_0\gamma/\tau)$ has no numerator zero (see Table 1), again assuming pilot manual feedback of glide-slope error d into thrust τ, one has a loop transfer function d/τ having three poles and no zero. Thus, a large pilot lead is necessary to obtain a comparable closed-loop bandwidth to that which would be available with front-side control. Without pilot lead, closed-loop stability is poor due to the lack of total system damping. These unfavorable facts are most pronounced in conventional aircraft without power effects ($Z_\tau = 0$), which have to be operated in either low front-side or back-side with RSS² or HGPC engaged.

Control Crossfeed

Assuming the back-side control technique, the undesirable characteristics previously mentioned in thrust response associated with RSS² or HGPC can be improved by control crossfeed. Figure 6 shows a block diagram for control crossfeed where Δ_t is the throttle input and $G_t/(T_\tau s + 1)$ is an approximation of the τ/Δ_t response. By crossfeeding throttle command with equivalent thrust lag $1/T_e$ (which is set equal to $1/T_\tau$) into attitude command, one has a crossfeed control law for the arbitrary choice of (K_{et}, K_{tt}) with $R_t = K_{et}/K_{tt}$

$$\begin{bmatrix} \theta \\ \tau \end{bmatrix} = \begin{bmatrix} 1 & R_t/G_t \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \theta_c \\ \tau_c \end{bmatrix} \quad (10)$$

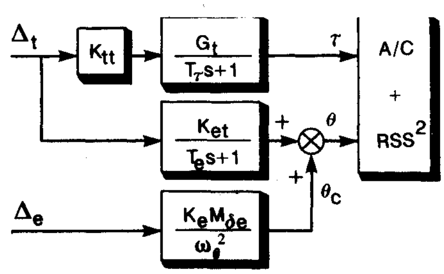


Fig. 6 Crossfeed of throttle command.

which produces equivalent control derivatives such that

$$X_\tau' = X_\tau + (X_\alpha - g)(R_t/G_t), \qquad Z_\tau' = Z_\tau + Z_\alpha(R_t/G_t) \tag{11a}$$

Numerators pertinent to thrust input are modified to give

$$N'^{u_a}_{\tau}(s) = X_\tau'(s + 1/T_{u\tau}'), \qquad 1/T_{u\tau}' = -Z_w + (Z_\tau'/X_\tau')X_w \tag{11b}$$

$$N'^{U_0\gamma}_{\tau}(s) = -Z_\tau'(s + 1/T_{\gamma\tau}'), \qquad 1/T_{\gamma\tau}' = -X_u + (X_\tau'/Z_\tau')Z_u \tag{11c}$$

while leaving denominator $\Delta(s)$ unaltered.

Since $\tan(\phi_t') = (-Z_\tau'/T_{\gamma\tau}')/(X_\tau'/T_{u\tau}')'$ arbitrary direction ϕ_t' can be assigned ranging from the original $\phi_t' = \phi_t$(when $R_t = 0$) to $\phi_t' = \phi_e + 180$ deg (when $R_t = \infty$). The magnitude $v_{ss} = [u_a^2 + (U_0\gamma)^2]^{1/2}$ can be adjusted as well. Substituting X_τ' and Z_τ' from Eq. (11a) with $Z_\tau = 0$, Eq. (11c) gives

$$1/T_{\gamma\tau}' = -X_u + (Z_u/Z_\alpha)[(X_\alpha - g) + X_\tau/(R_t/G_t)]$$

$$= 1/T_{\gamma\theta} + (Z_u/Z_\alpha)X_\tau/(R_t/G_t) \tag{11d}$$

A zero, $1/T_{\gamma\tau}'$, of transfer function $(U_0\gamma/\tau_c)$, is now produced by the control crossfeed, and its value can be arbitrarily assigned to a positive value irrespective of the sign of $1/T_{\gamma\theta}$ by using a positive R_t/G_t since $(Z_u/Z_\alpha)\ X_\tau > 0$.

Static Decoupling of Throttle Response

A case is of particular interest when a choice $R_t/G_t = X_\tau/g$ is made. Under this condition (superscript asterisk is used instead of prime); one has, from Eq. (11a), $X_\tau^* = X_\alpha(X_\tau/g)$ and $Z_\tau^* = Z_\alpha(X_\tau/g)$ so that Eqs. (11b) and (11c) are rewritten as

$$N^{*u_a}_{\tau}(s) = X_\tau^* s, \qquad 1/T_{u\tau}^* = 0 \tag{12a}$$

$$N^{*U_0\gamma}_{\tau}(s) = -Z_\tau^*(s + 1/T_{\gamma\tau}^*), \qquad 1/T_{\gamma\tau}^* = -X_u + (X_\alpha/Z_\alpha)Z_u = 1/T_{\theta 1} \tag{12b}$$

which must be compared with the second row of Table 1. Especially, Eq. (12a) indicates $\phi_t^* = 90$ deg. Additional comments follow.

1) Since the zero defined by Eq. (12b) cancels the $1/T_{\theta 1}$ pole, $(U_0\gamma/\tau_c)^* = -Z_\tau^*/(s + 1/T_{\theta 2})$ is obtained, which contrasts with the original RSS[2] system in Table 1. From the standpoint of pilot manipulation, throttle control must work adequately for height control. As a matter of fact, assuming pilot proportional feedback $d \to \tau$ with a reasonable gain K_d and without any lead, a pair of closed-loop poles (ζ_d^*, ω_d^*) of acceptable bandwidth is defined by roots of characteristic polynomial

$$\Delta^*_{c(d\to\tau)}(s) = s\Delta(s) + K_d N^{*d}_{\tau}(s) = (s + 1/T_{\theta 1})\Delta^*_{d\to\tau}(s)$$

where

$$\Delta^*_{d\to\tau}(s) = s(s + 1/T_{\theta 2}) - K_d Z_\alpha(X_\tau/g)$$

$$= s^2 + 2\zeta_d^*\omega_d^* s + \omega_d^{*2} \tag{13a}$$

2) Since the $(u_a/\tau_c)^*$ response at steady state is suppressed, throttle movements will excite no air-speed excursions, at least in the low-frequency range, and therefore attitude command becomes an exclusive device for air-speed control. The throttle crossfeed into attitude command does not alter the $(u_a, U_0\gamma)$ responses to column input, and since the (u_a/θ) transfer function of the original RSS[2] system has sufficiently high dc gain (see Table 1), pilot-loop closure $u_a \to \theta$ with a rather low gain K_θ would suffice to get a tighter air-speed control. Even when pilot-loop closure $d \to \tau$ exists, $(u_a/\theta)^*_{d\to\tau}$ response characteristics remain almost unaltered. This can be shown as follows. When $\phi_t = 90$ deg, since the coupling numerator is given by $N^{*u_a d}_{\theta\ \tau}(s) = X_\tau Z_\alpha$,

$$N^{u_a}_{\theta}(s) + K_d N^{*u_a d}_{\theta\ \tau}(s) = (X_\alpha - g)\ s(s + 1/T_{u\theta}) + K_d X_\tau Z_\alpha$$

$$\approx -g\ \Delta^*_{d\to\tau}(s) \tag{13b}$$

is obtained where the included approximation is justified because of $1/T_{u\theta} \approx 1/T_{\theta 2}$ and $X_\alpha - g \approx -g$. Cancellation of $\Delta^*_{d\to\tau}(s)$ between Eqs. (13a) and (13b) yields $(u_a/\theta)^*_{d\to\tau} \approx (u_a/\theta)$.

3) Finally, after both feedback loops $d \to \tau$ and $u_a \to \theta$ are closed at the same time, from Eqs. (13a) and (13b) one has

$$\Delta^*_{c(d\to\tau,u_a\to\theta)}(s) = \Delta^*_{c(d\to\tau)}(s) + K_\theta\{N^{u_a}_{\theta}(s) + K_d N^{*u_a d}_{\theta\ \tau}(s)\}$$

$$\approx [(s + 1/T_{\theta 1}) - K_\theta g]\ \Delta^*_{d\to\tau}(s) \tag{14a}$$

and

$$N^{*d}_{\tau}(s) + K_\theta N^{*u_a d}_{\theta\ \tau}(s) = -Z_\alpha(X_\tau/g)(s + 1/T_{\theta 1}) + K_\theta X_\tau Z_\alpha$$

$$= -(Z_\alpha X_\tau/g)[s + 1/T_{\theta 1} - K_\theta g] \tag{14b}$$

When Eq. (14b) is divided by Eq. (14a), their factors (in brackets) cancel each other, yielding $(d/\tau)^*_{d\to\tau,u_a\to\theta} = (d/\tau)^*_{d\to\tau}$.

4) As a summary, if $\phi_t = 90$ deg, two loop closures $u_a \to \theta$ and $d \to \tau$ do not interfere with each other, and pilots can adaptively adjust both gains $K_d(>0)$ and $K_\theta(<0)$ in an arbitrary and independent manner. The resulting pilot-vehicle closed loop will be expressed by

$$(d/d_{\text{cmd}})^*_c = -K_d Z_\alpha(X_\tau/g)/\Delta^*_{d\to\tau}(s), \qquad K_d d_{\text{cmd}} = \tau_{c_{\text{cmd}}} \tag{15a}$$

$$(u_a/u_{a_{\text{cmd}}})^*_c = -K_\theta g/(s + 1/T_{\theta 1} - K_\theta g), \quad K_\theta u_{a_{\text{cmd}}} = \theta_{c_{\text{cmd}}} \tag{15b}$$

This feature is important because feedback $u_a \to \theta$ reproduces an effective M_u, and pilots must adjust their feedback gain K_θ so that the tightness of the air-speed control and gust response θ/u_g are compromised.

Flight-Test Results and Discussion

Figure 7 shows typical step responses in the $u_a - U_0\gamma$ state plane with the original RSS[2] ($\phi_t = 18$ deg) and with the control crossfeed ($\phi_t = 90$ deg). Computed predictions are compared with the measurements $(u_a, U_0\gamma)$ obtained during flight tests after correction of gust components (u_g, w_g). Only acceptable levels of errors are seen between computations and corrected measurements.

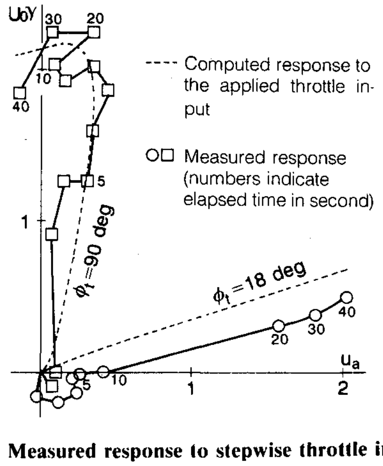


Fig. 7 Measured response to stepwise throttle input.

A series of flight tests for glide-slope tracking were conducted to verify the effects of control crossfeed with various combinations of steady-state vector angle ϕ_t and equivalent throttle effectiveness ν_{ss}. Tasks for the evaluating pilot were the same as those stated previously. Of the total of four evaluating pilots, one had much more flight experience in helicopters than fixed-wing craft whereas the others were pilots of fixed-wing craft. First, each pilot was requested to determine his best throttle effectiveness (ν_{ss} per unit throttle lever displacement) which was used during the following tests.

Figures 4c and 4d show time histories of a typical glide-slope tracking with control crossfeed ($\phi_t = 90$ deg). In Fig. 4c, a fixed-wing aircraft pilot applied the back-side control technique after full familiarization. In contrast to the original RSS^2 case of Fig. 4b, where another fixed-wing pilot used the front-side piloting technique, the pilot applied only throttle input for capturing the glide slope without unnecessary coordinations in column input. Because the decoupling of responses to throttle is only static, or of low frequency, some excitations in air speed due to rapid throttle movements are still seen. The speed excursions are of low level, however, when compared with Fig. 4b. Some small but quick column movements are observed. They seem to respond to the small air-speed variations and rather look like "manual control."

Figure 4d is an example of glide-slope tracking with a control crossfeed of $\phi_t = 90$ deg performed by the helicopter pilot. In this particular case, some off-trim conditions existed before the glide-slope capture, which the pilot tried to stabilize using attitude commands. Actually he preferred to use beep-trim rather than column, and the resulting column movements look like "supervisory control" as is the case of the throttle movements in Fig. 4b. Apparently the threshold of air-speed excursions is pilot dependent and, in this case, is about ± 1 m/s.

Pilots' ratings[16] are plotted in Fig. 8 against the tested steady-state vector angles ϕ_t with discrimination of pilot control techniques, either front-side or back-side, based on their statements. Although some scattering exists, the following is observed from the figure: 1) Ratings deteriorate for a ϕ_t of <45 deg where mainly the front-side control technique is used by pilots. The original RSS^2 case ($\phi_t = 18$ deg) is not rated good. 2) Somewhat better ratings are given for $\phi_t = 90$ deg than others, specifically when the back-side control technique (solid symbols) is used. 3) Ratings are slightly worse at $\phi_t = 130$ deg or more where no preference of control techniques is obvious.

Taking the pilots' comments into account, additional observations are obtained: 4) The helicopter pilot (square symbols) had a clear preference for $\phi_t = 90$ deg right after his first approach. 5) Fixed-wing pilots seemed to have rather ambiguous ratings for ϕ_t values, at least during their earlier test flights. 6) Two of the fixed-wing pilots had better ratings for $\phi_t = 90$ deg after being familiarized with the back-side piloting technique.

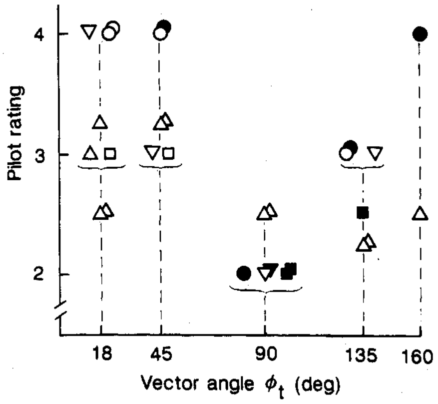


Fig. 8 Pilot ratings (solid symbols: back-side technique/otherwise front-side, square symbol: helicopter pilot/otherwise fixed-wing pilot).

Table 2 Tracking performance, control cost, and estimated gust during typical glide-slope tracking flight tests

RMS values[a]	$\phi_t = 18$ deg Pilot F[b] (*f*)[c]	$\phi_t = 18$ deg Pilot H ($f + b$)	$\phi_t = 90$ deg Pilot F (*f*)	$\phi_t = 90$ deg Pilot F (*b*)	$\phi_t = 90$ deg Pilot H (*b*)
u_a, m/s	0.85	1.12	0.97	0.74	0.77
d, dot	0.31	0.36	0.20	0.24	0.18
Δ_e, mm	2.91	3.96	2.10	0.65	1.20
Δ_t, mm	1.28	1.28	0.99	0.90	0.58
$(u_g^2 + w_g^2)^{1/2}$, m/s	1.6	1.4	2.3	0.8	2.8

[a]RMS values are evaluated after subtraction of mean values; data before glide-slope capture are excluded.
[b]F/H indicates the fixed-wing/helicopter pilot, respectively.
[c]Symbols (*f*)/(*b*) indicate front-side/back-side control techniques, respectively, upon pilot's statement.

Tracking errors in glide slope and air speed, control costs in column and throttle movement, and estimated gust magnitude, all given in root-mean-square values, are summarized in Table 2. The contents of the table are not statistical results but represent typical flight cases. It still seems to imply that a smaller tracking error was obtained by a smaller amount of manipulator movements when the back-side control technique is used with $\phi_t = 90$ deg rather than with $\phi_t = 18$ deg. Generally, less manipulator movement does not necessarily mean a smaller pilot work load, but in these cases, a smaller control cost plus a smaller tracking error resulted in better ratings.

From the preceding reasonings, it must be understood that the apparent drawback of RSS^2 and HGPC, i.e., control cross coupling, may be coped with by a simple control crossfeed. In the present configurations of VSRA, a standard pitot system and a very light-weight and high-frequency responsive vane were used for air-data measurements and feedback control. In practical applications, safety features of the feedback loop need to be considered. When operating points such as U_0 and/or γ_0 are not fixed in practical applications, gain scheduling becomes necessary to implement the RSS^2 control law as given by Eqs. (3), (4a), and (4b). The methodologies are, however, beyond the scope of the present discussion.

Conclusions

A new pitch-mode decoupling system, including air-data feedback into an elevator, was proposed. Flight tests using an experimental airplane with the system engaged revealed the following: 1) The necessary bandwidth of 3 rad/s was obtained in the decoupled pitch mode with no annoyance caused by possible instability of any dynamic mode, while the elevator servo had a cutoff frequency of as low as 6.3 rad/s. 2) The response to gust disturbances in the decoupled pitch mode was suppressed as predicted, and the pilot's remnant in man-vehicle closed loop decreased during the glide-slope tracking task. 3) Cross coupling of thrust and pitch-attitude commands into air speed and flight path adversely affect the precision glide-slope tracking task where air-speed excursions are apt to be induced.

To cope with the speed excursions, an appropriate crossfeed from throttle command into attitude command was proposed. Flight-test results verified that when the low-frequency air-speed response to thrust command is suppressed by control crossfeed, both flight-path and air-speed controls became easier. By applying the back-side control technique, three out of four pilots rated the scale of 2 with the control crossfeed, whereas the ratings ranged from 2.5 to 4 with the decoupling system only.

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