Factors Governing Control in a STOL Landing Approach

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A combined analytic and ground-based simulator investigation has been conducted to identify the vehicle parameters and factors governing *manual* control in an STOL approach situation. In this effort, emphasis was on the path control restrictions which are independent of short-period attitude control aspects. Generic and specific closed-loop analyses are applied to identify the crucial vehicle parameters and to predict suitable control techniques. From these analytic efforts test configurations were selected for the simulator evaluations to verify the predictions. Results of the experiments confirm that the path control problems are characterized by the nature of the airspeed (u) and altitude (h) response to the pertinent pilot inputs. For powered-lift STOL aircraft the inherent path control problems stem from coupling effects (e.g., thrust inclination and high α-induced drag, that is, large X_w). Pilot background and experience was also found to play a role in the acceptability of a given technique and in the over-all ability to control path.

Nomenclature

$A_{\dot{h}}$	= altitude rate gain with speed control crossfeed
g	= gravitation acceleration
h	= altitude
I_y	= moment of inertia about y-axis
m	= vehicle mass; vehicle or controlled element motions in general
M	= sum or aerodynamic and thrust pitching moments divided by moment of inertia; i.e., pitching acceleration
M_λ	= $(1/I_y)(\partial M/\partial\lambda)\lambda$ where $\lambda = u, w, \delta_e$ or δ_T
${}^\lambda N_\delta(s)$, ${}^\lambda N_\delta$	= controlled element transfer function numerator polynomial, particularized by substituting a variable for $\lambda = u, w, h$; $\delta = \delta_e, \delta_T, \theta_c$
${}^{\lambda_1\lambda_2}N_{\delta_1\delta_2}(s)$, ${}^{q_1q_2}N_{\delta_1\delta_2}$	= controlled element transfer function coupling numerator polynomial, particularized by substituting appropriate variables for q_1 and q_2 (e.g., u, w, h) and δ_1 and δ_2 (e.g., $\delta_e, \delta_T, \theta_c$)
s	= dependent variable for the Laplace transform
t	= time
T	= thrust
T_λ	= time constant, particularized by the subscript λ; where $\lambda = \theta, u, w, h$
$T_{\lambda i}$	= time constant particularized by mode designation where $\lambda i = \theta 1, \theta 2, u\theta, h\theta, h1$
u	= velocity perturbation along x-axis
U	= velocity component along x-axis
w	= normal (z) component of perturbed translational velocity of vehicle or controlled element
x,y,z	= body-fixed axis system, x positive forward, y positive out the right wing, z positive down
X	= sum of aerodynamic and thrust forces along x-axis divided by mass
X_λ	= $1/m(\partial X/\partial\lambda)$ where $\lambda = u, w, \alpha, \delta_e$ or δ_T
$Y_{p\lambda}$	= pilot controlled element transfer function for feedback of variable λ
Z_λ	= $1/m(\partial Z/\partial\lambda)$ where $\lambda = u, w, \alpha, \delta_e$ or δ_T
α	= angle of attack
Δ	= longitudinal characteristics determinant, denominator for longitudinal transfer functions
ζ_λ	= damping ratio or second-order factor, particularized by the subscript λ; where $\lambda = \theta$
ω_λ	= undamped natural frequency of second-order factor or mode, particularized by subscript λ, where $\lambda = \theta$

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Introduction

DESPITE the interest in STOL aircraft shown over the past decade, the principles of manually controlling them in the powered-lift flight region are not well understood. This paper describes both the results and the theoretical considerations behind a specially-designed experiment where the objective was to explore and identify basic problems pertinent to manual approach control of STOL aircraft. These problems stem from the effects of certain crucial stability and control parameters which govern the nature of the relative airspeed (u) and climb ($\dot{h}$) responses to the pilot control inputs. In particular, this coupling of the controls is most pronounced due to the effective thrust inclination, offset, and high α-induced drag. This "contamination" of responses can sometimes be alleviated by a change in control technique, i.e., by the pilot's using an alternative set of inputs for the primary control of u or $\dot{h}$. The extent that such strategy changes in control technique provides an acceptable solution depends on whether the resulting u and $\dot{h}$ responses are thereby purified, or if still contaminated, whether they are separated by the pilot because of their difference in frequency (or response-time) content.

Viewed in this light, the problems of STOL path control boil down to questions concerning the allowable (limit) coupling characteristics of "secondary" and primary motions. However, since the degree of coupling encountered is in general a function of the piloting technique employed, there are further questions as to the dependence of technique on coupling and allowable coupling on technique.‡ In approaching this dependency, both generic and specific closed-loop pilot/vehicle analyses have been employed. These analyses are based on methods and pilot models which have been utilized in similar connection for the past ten years.[1,4,5] Consequently, in this paper the results of such efforts are presented without explanation in deference to illustrating how such efforts identified the governing parameters and explained the experimental results.

‡Piloting technique is not to be confused with skill. In our context, technique relates to the sensible loop structure utilized, as discussed later.

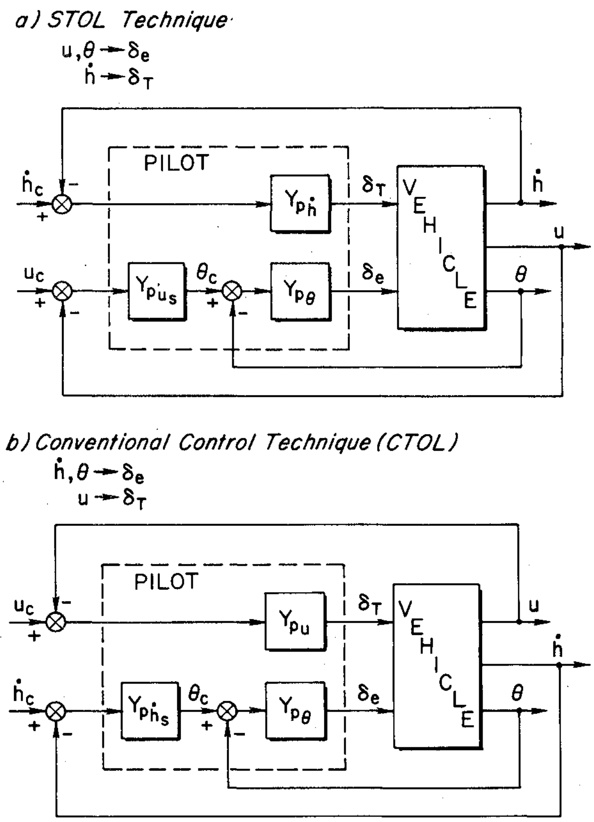

Fig. 1. Two piloting techniques.

Governing Parameters for Path Control

The basic theoretical aspects underlying manual path control and governing vehicle parameters may be evolved from an examination of the two prevalent piloting techniques, as represented schematically by the block diagrams of Fig. 1. For either technique the inner, attitude, loop is fundamental; however, the specific requirements on the tightness or other qualities of this loop will vary with the outer-loop control technique employed. For example, for conventional (CTOL) control of $\dot{h}$ with attitude, the closed inner-loop bandwidth (a measure of closed-loop response time) must be sufficiently high to permit fairly rapid corrections in $\dot{h}$. By way of contrast, for unconventional (STOL) control of $\dot{h}$ with thrust and u control with θ, the normally-expected, and encountered, low-frequency u deviations theoretically permit some relaxation of the inner-loop bandwidth. For this technique the primary requirement on the θ loop is to provide phugoid damping and counter thrust (or gust) induced moments.

Regardless, we may normalize the attitude control aspects and thus concentrate on the outer-loop path $(u,\dot{h})$ control problems by considering the attitude as constrained. Under these conditions of *constrained* attitude, the pertinent dynamics of the aircraft's motions are given by the attitude *numerator,* i.e., the closed, inner-loop denominator, Δ', given in general by:

$$\Delta' = \Delta + Y_{p\theta}\,{}^{\theta}N_{\delta e}$$

approaches $Y_{p\theta}\,{}^{\theta}N_{\delta e}$ for the large $Y_{p\theta}$ (and $\theta \to \theta_c$) in the frequency region of interest (implicit in attitude stabilization). Similar effects occur for the usual control transfer function numerators. The net result, also true (but less consistently so) for tight manual control of attitude, is that the pertinent *path* control transfer functions are given rather simply in terms of the following forms and factors (for $\gamma_0 = 0$§):

Characteristic

$$\Delta = Y_{p\theta}\,{}^{\theta}N_{\delta e} = [s^2 + (-Z_w - X_u)s + (Z_w X_u - X_w Z_u)]$$
$$= s^2 + 2\zeta_\theta\omega_\theta s + \omega_\theta^2 \qquad (1a)$$

or

$$(s + 1/T_{\theta 1})(s + 1/T_{\theta 2})$$

The latter form results if X_w is small or in general if $|X_w Z_u| \ll |Z_w X_u|$, then:

$$\Delta \doteq (s - X_u)(s - Z_w) \qquad (1b)$$

with $1/T_{\theta 1} \doteq -X_u$ and $1/T_{\theta 2} = -Z_w$.

Attitude Command Responses, assuming $X_{\delta e} = Z_{\delta e} = 0$, are correspondingly given by:

$$\frac{u}{\theta_c} = \frac{1}{\Delta}(X_\alpha - g)\left(s + \frac{gZ_w}{X_\alpha - g}\right) = \frac{1}{\Delta}(X_\alpha - g)\left(s + \frac{1}{T_{u1}}\right) \qquad (2)$$

where $1/T_{u1} = gZ_w/(X_\alpha - g)$.

$$\frac{\dot{h}}{\theta_c} = \frac{Z_\alpha}{\Delta}\left[s - X_u + \frac{Z_u}{Z_w}\left(X_w - \frac{g}{U_0}\right)\right] = \frac{Z_\alpha}{\Delta}\left(s + \frac{1}{T_{h1}}\right) \qquad (3)$$

where $1/T_{h1} = [-X_u + (Z_u/Z_w)(X_w - g/U_0)]$ (backside term).

Throttle Responses with $M_{\delta T} = 0$ become:

$$\frac{u}{\delta_T} = \frac{X_{\delta T}}{\Delta}\left[s - Z_w + X_w\left(\frac{X_{\delta T}}{Z_{\delta T}}\right)\right] = \frac{X_{\delta T}}{\Delta}\left[s + \frac{1}{T_{u\theta}}\right] \qquad (4)$$

where $1/T_{u\theta} = -Z_w + X_w(X_{\delta T}/Z_{\delta T})$.

$$\frac{\dot{h}}{\delta_T} = -\frac{Z_{\delta T}}{\Delta}\left[s - X_u + Z_u\left(\frac{X_{\delta T}}{Z_{\delta T}}\right)\right] = -\frac{Z_{\delta T}}{\Delta}\left(s + \frac{1}{T_{h\theta}}\right) \qquad (5)$$

where $1/T_{h\theta} = -X_u + Z_u(X_{T}/Z_{\delta T})$.

Notice from the above relationships that the characteristic Δ path mode roots for the closed-loop attitude situation are defined by the basic aircraft lift and drag terms, Z_w and X_u, plus the coupling terms, X_w and Z_u. The latter derivatives are responsible for the degree of coupling existing between the speed and flight path modes, since they define the corrupting force produced by the desired motion in either the vertical or axial direction. That is, the drag change with vertical motion, X_w, establishes how

§ The $\gamma_0 = 0$ 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_0 pertinent to approach conditions.

¶ Because of the constrained attitude effect, the u and $\dot{h}$ throttle-response numerators are not the usual simple δ_T numerators but rather the coupling numerators which apply when two (or more) control inputs are involved, hence the modified notation which reflects conventional multiloop practice.[4]

speed will vary when the aircraft changes flight path or rate of climb (i.e., w) and vice versa for the Z_u term. When the product of these two terms is large and negative the path mode is oscillatory ($\omega_\theta{}^2$); when the product is small the path modes are two first-order subsidences ($1/T_{\theta 1}$, $1/T_{\theta 2}$). Because the control-input transfer function numerators Eqs. (2-5) are all first order, there can be no true cancellation of (selective) poles and zeros when the path mode is oscillatory. The result is that u and $\dot{h}$ motions then occur with the same dynamics and are therefore inherently coupled. However, the relative magnitudes of u and $\dot{h}$ are also important; and these are governed, for the throttle inputs, by the ratio $X_{\delta T}/Z_{\delta T}$.

The consequences of coupled u and $\dot{h}$ responses are best illustrated by visualizing the control actions and responses associated with the two piloting techniques for a level of $X_w Z_u$ coupling which produces an oscillatory characteristic (ω_θ). Considering the CTOL technique, $\dot{h} \rightarrow \theta_c$** and $u \rightarrow \delta_T$, the time-history sketch (Fig. 2) shows that for a near step attitude input the $\dot{h}$ response is more rapid and proportionately much greater than the corresponding u response (both $\dot{h}$ and u are sketched to the same scale). In fact, there is essentially no u response in the first 3 to 4 sec, implying a very speed stable situation (due to the positive X_w required to produce the coupled, ω_θ, conditions). The final value of the speed change is conventional in that there is a reasonably small reduction for a nose-up attitude. Thus, from the standpoint of flight path control, $\dot{h} \rightarrow \theta_c$ appears direct and adequate. That is, u responses are decoupled from $\dot{h}$ responses, despite their oscillatory similarity, because of magnitude differences. Accordingly, provided speed error remains acceptably small, there are no anticipated control problems. However, it is apparent that because of its delayed response characteristics precise u control with attitude (e.g., to correct for winds) would be difficult; furthermore, such corrections will introduce large flight path errors.

Considering, therefore, speed control with throttle, we see that except for the short delay in $\dot{h}$ response the $\dot{h}$ and u traces are very similar. That is, there is essentially no way of making a throttle-controlled speed correction without introducing altitude rate errors of equal magnitude. Physically, this interaction or coupling between u and $\dot{h}$ is obvious, since with the thrust aligned along the stability axis ($\theta_T = 0°$) an $\dot{h}$ change is produced by a normal force change due to $Z_u u$ (i.e., $\dot{h} = Z_u u$).

Changing techniques, i.e., controlling $\dot{h}$ with throttle and u with θ, only makes the situation more difficult because of the very poor u and associated large secondary $\dot{h}$ response. The pilot effectively has no direct measure of speed regulation for either technique.

At the other extreme, and to illustrate the direction of the pertinent transfer functions, consider the inherently decoupled path mode condition ($1/T_{\theta 1}$, $1/T_{\theta 2}$). The purity of the individual transient response to throttle inputs is governed additionally by the values of $1/T_{u\theta}$ and $1/T_{h\theta}$. These zeros are affected by the inherent coupling derivatives, X_w and Z_u, and also by the ratio of the control force derivatives as shown specifically by Eqs. (4) and (5). Without the corrupting effect of these coupling terms on the dynamics [i.e., for $X_w = X_{\delta T}/Z_{\delta T} = 0$], the $\dot{h}$ path response to a throttle input, as previously given [Eqs. (1) and (4)], is:

$$\frac{\dot{h}}{\delta_T} = \frac{-Z_{\delta T}(s + 1/T_{h\theta})}{(s + 1/T_{\theta 1})(s + 1/T_{\theta 2})}$$

**This notation is used, for rigor, to denote that θ, as controlled by the stick through the attitude command and stabilization system, is the controlling input in accordance with the block diagrams of Fig. 1. The transfer functions, h/θ_c and h/δ_e (attitude constrained), are identical.

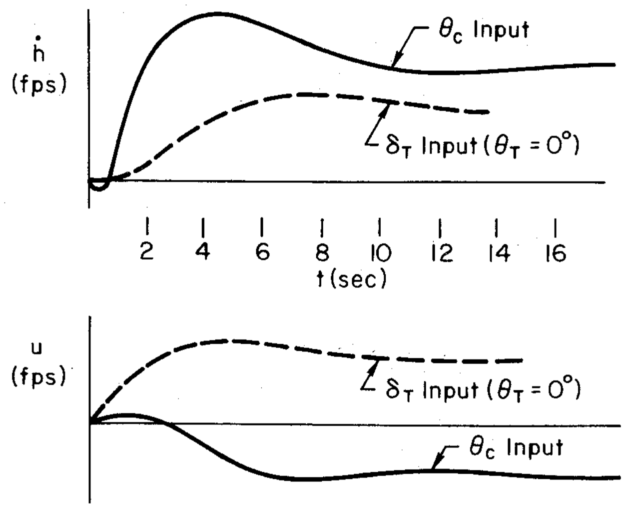

Fig. 2 Speed and altitude rate response to step attitudes and throttle inputs.

where, now,

$$\frac{1}{T_{h\theta}} = -X_u = \frac{1}{T_{\theta 1}} \qquad (6)$$

thus

$$\frac{\dot{h}}{\delta_T} = \frac{-Z_{\delta T}}{s + 1/T_{\theta 2}}$$

The corresponding u/δ_T is, of course, identically zero, because $X_{\delta T}$ is zero; however, for finite (but small) $X_{\delta T}$, $u/\delta_T \doteq X_{\delta T}/(s + 1/T_{\theta 1})$. The point is both responses are of different magnitude and frequency content, and this desirable feature of *uncoupled* path modes depends strongly on near-cancellation of certain numerator and denominator factors. Without such near-cancellation inherent decoupling, as defined by well separated values of $1/T_{\theta 1}$ and $1/T_{\theta 2}$, may be only a promise and not a reality.

Similar but incomplete pole-zero cancellation and resultant separation of u and $\dot{h}$ responses occur for stick inputs and the above-postulated conditions; i.e., for $X_w = 0$, $1/T_{u1} = -Z_w = 1/T_{\theta 2}$ and $1/T_{h1} = -X_u - (g/U_0)(Z_u/Z_w) = 1/T_{\theta 1} - (g/U_0)(Z_u/Z_w)$. Accordingly:

$$\frac{u}{\theta_c} = \frac{X_\alpha - g}{s + 1/T_{\theta 1}}$$

$$\frac{\dot{h}}{\theta_c} = \frac{Z_\alpha(s + 1/T_{h1})}{(s + 1/T_{\theta 1})(s + 1/T_{\theta 2})} \qquad (7)$$

where

$$\frac{1}{T_{h1}} = \frac{1}{T_{\theta 1}} - \frac{g}{U_0}\left(\frac{Z_u}{Z_w}\right)$$

Although the u response is pure and slowly subsident ($1/T_{\theta 1}$), the $\dot{h}$ response while basically fast ($1/T_{\theta 2}$) can also exhibit the same slow subsidence. Whether it does so depends on the difference between (more precisely on the ratio of) $1/T_{h1}$ and $1/T_{\theta 1}$. If $1/T_{h1}$ is small and positive, as usually true for $1/T_{\theta 1}$, the slow subsidence is essentially removed from the $\dot{h}$ response, which is then similar to that for throttle input [Eq. (3)]. If $1/T_{h1}$ is negative, the magnitude of the subsident contribution is increased and the speed bleedoff effect eventually produces a reversal in the sign of the $\dot{h}$ response. This is a well-known effect of operating on the backside of the thrust-required (or drag minus thrust) curve,[2-4] and $1/T_{h1}$ is directly related to the slope of this curve at the trim speed. Another, not so well-appreciated, fact is that $1/T_{h1}$ and $1/T_{\theta 1}$ can combine to limit the peak (short-time) $\dot{h}$ response to values considerably less than $U_0\theta^2$, the

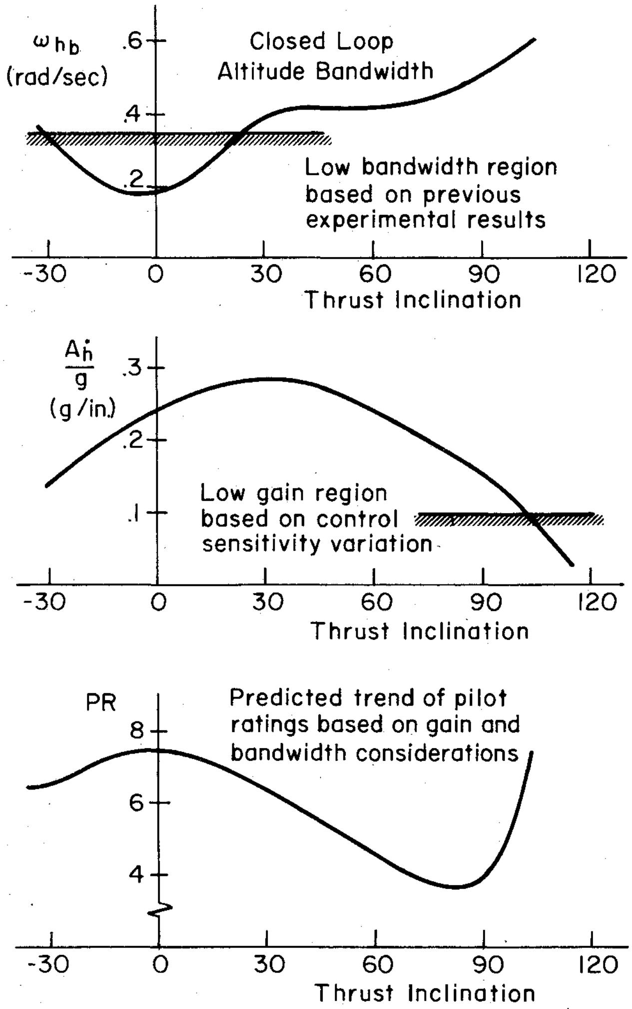

Fig. 3 Closed-loop analysis of path control; X_w = 0 ($1/T_{h1}$ = −0.09).

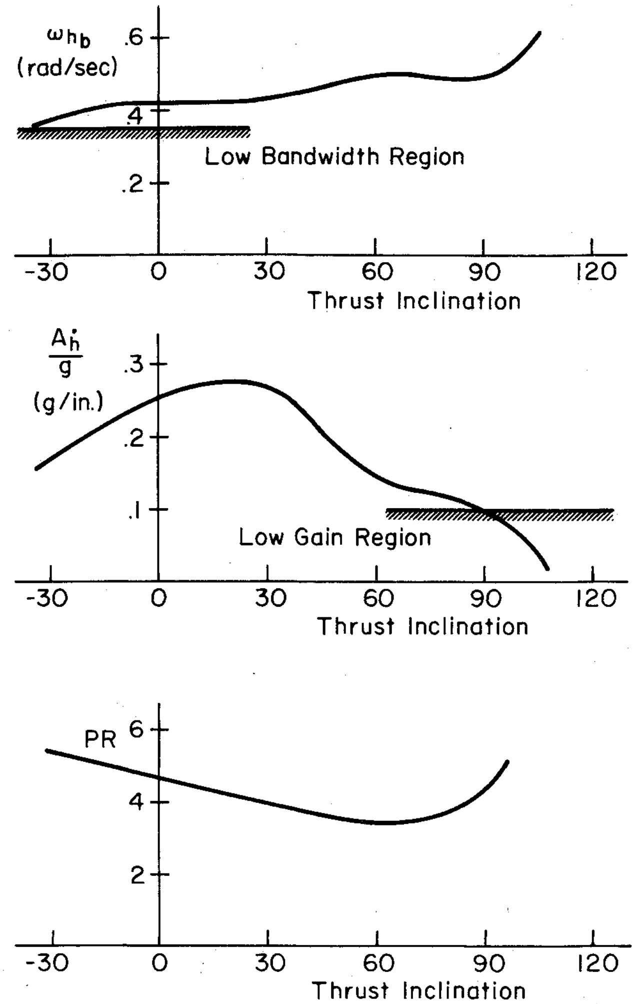

Fig. 4 Closed-loop analysis of path control; X_w = 0.01 ($1/T_{h1}$ = −0.03).

truly decoupled value (i.e., when $1/T_{h1} \doteq 1/T_{\theta 1}$. Notice too that the initial h/u response ratio is given by Z_α/g, a handling quality parameter most often used to characterize *short-period response*.[9] However, in effect, the relation appears to be setting limits on the separation between the u and $\dot h$ responses for elevator control. Thus, path control may be an underlying factor in the current short-period dynamic requirements defined in Ref. 9. Finally, we should note [Eqs. (1) and (3)] that the values of $1/T_{h1}$ and $1/T_{\theta 1}$ cannot be varied independently without also modifying the inherent attitude numerator; i.e., the basic derivatives, X_u, Z_u, X_w, Z_w, all appear in both $\omega_\theta{}^2$ and $1/T_{h1}$.

The foregoing discussion has provided a physical accounting of the multiloop path control techniques indicated by the diagrams of Fig. 1. A more quantitative appreciation of the effects of the governing parameters on performance capability of these techniques has been gained by application of the closed-loop pilot/vehicle analysis methods summarized in Refs. 1, 4, and 8. For example, the effect on closed-loop performance merits of thrust inclination, $X_{\delta T}/Z_{\delta T}$, and dynamic coupling, X_w, for a fixed value of Z_u is shown in Figs. 3 and 4. The performance merits used are the effective altitude closure bandwidth, ω_h, and gain, A_h. The variation of ω_h and A_h is given as a function of thrust inclination for two values of X_w (i.e., X_w = 0 and 0.1). The corresponding backside conditions are $1/T_{h1}$ = −0.09 and −0.03, respectively. The detailed aspects of these closures are described in Ref. 12; however, for each condition the bandwidth and gain were computed assuming that the pilot closed the $h \rightarrow \delta_T$ loop with an ideal crossfeed to maintain effectively zero speed error. This $h \rightarrow \delta_T]_{(\theta CF \rightarrow u)}$ was closed with a crossover of 0.5 rad/sec and a closed-loop bandwidth defined which gave 45° of phase margin.

We will not dwell further on the closure details since the prime concern is trend of the performance merits as thrust inclination changed. Notice that thrust angles between 90° and 0° show a progressive reduction in ω_h while the gain A_h, in general, increases. An increase in bandwidth would be expected to improve performance; however, an excessive increase in gain (i.e., sensitivity) tends to degrade performance. Thus, the two merits appear at first glance to be somewhat contradictory. Fortunately, this is *not* the case. For, in fact, a high gain condition in combination with a low bandwidth is a rather poor control situation, combining the undesirable features of a sluggish response with a highly sensitive control. Thus, the trends shown are indicative of progressively poorer control properties. Pilot's control under these conditions is characteristically poor because the vehicle doesn't respond rapidly enough for good regulation (e.g., suppression of disturbances), and with high sensitivity there is a strong tendency for a PIO (i.e., pilot-induced oscillation).

Considering the above factors, an estimated pilot rating trend is shown for each condition. The predicted trends imply that the best pilot ratings occur at the higher inclinations. Note also that for $1/T_{h1}$ = −0.09, the extreme backside condition, the variation in rating is more severe (i.e., varying from satisfactory to unacceptable), with the best rating occurring at 90°. Accordingly, based on these theoretical considerations, we would anticipate the pilot rating trends as given in Figs. 3 and 4 for the specified conditions of thrust inclination and backsidedness.

Experimental Design

The experimental design reflecting the theoretical background exposed in the preceding section is covered briefly in the following. In general, the effects of the various degrees of dynamic and control coupling on manual path control were explored, independent of short-period characteristics, using selected variations in the dynamic and throttle control coupling terms. These variations were accomplished, respectively, through changes in the incremental drag with angle of attack, X_w, and in the thrust inclination (i.e., $X_{\delta T}/Z_{\delta T}$). The vertical force change due to speed, Z_u, was maintained at a fixed value throughout the test.

Such changes in coupling terms effectively simulated modification of the aircraft's total trim lift/drag characteristics. Total in this case refers to the combined aerodynamic and thrust forces. Since the trim characteristics are strongly configuration-related, the cross section of parameter variations are considered somewhat equivalent to various medium weight transport aircraft types having different lift/drag characteristics but trimmed at the same flight conditions (e.g., along a −7.5° glide slope at 60 knots).

The NASA Ames Research Center S-16 three-degree-of-freedom moving-cab transport simulator was used to provide a limited but realistic motion environment. Conventional transport instrumentation and controls (i.e., control wheel and rudder pedals) were employed with basic raw guidance information furnished by standard crosspointed needles. A glide slope beam of ±1° in depth and a localizer beam of ±43° width were simulated; these correspond to an ILS instrument sensitivity of 0.5° per dot glide slope error and 3° per dot localizer error.

Tasks and Test Matrix

A simulated straight-in instrument (ILS) landing approach was the single task performed by the pilots during this study. This approach was initiated on the localizer beam from an off-nominal glide slope situation which corresponded to a path parallel to and 100 ft below a −7.5° ILS beam at about a 1500-ft altitude. The initial trim speed was 60 knot. This intentionally-biased starting point in position required a corrective maneuver by the pilot similar to that associated with a normal glide slope interrupt. This low condition was indicated by the ILS needles and the pilots were requested to correct the indicated off-condition as quickly as possible. In addition, they generally introduced their own disturbances, offsets, and abuses to aid their evaluation. The lateral ILS task was simply to maintain the localizer beam.

The continuous random turbulence used in this study conforms to the Dryden turbulence forms given in Refs. 6 and 9. Both translational and rotational gust components about longitudinal and lateral axes were introduced. The level of turbulence provided corresponded to a vertical rms gust, $\sigma_w = 3$ fps, based on an average altitude of 500 ft.

The matrix of test configurations examined in this experiment is given in Table 1. The dimensional derivations and the effective linear dynamic characteristics indicated in the table are based on constant coefficient perturbations about the 60 knot nominal trim condition. The particular "nominal" conditions shown in Table 1 provide a representative cross section of STOL-type transport vehicle dynamic and control characteristics. In particular, the basic dynamics of configurations 1–6 are typical of a tilt wing propeller STOL, while configurations 7–12 are more representative of current thrust augmented vehicles (e.g., augmentor wing concept or deflected thrust arrangement). Configurations 13–18 represent an extreme of the trend established by the first two sets.

The path control characteristics (i.e., u and $\dot{h}$ responses) for the throttle were governed by the effective thrust inclination, which was varied from the near vertical (90°) and from the near horizontal condition for each basic dynamic configuration. The attitude control response was held constant by using a rate-command attitude hold augmentation scheme. In selecting the thrust angle, certain levels of coupling between the speed and altitude rate or flight path were desired. That is, the responses were either coupled (i.e., both u and $\dot{h}$ had essentially the same response for a given input) or purified (decoupled, i.e., throttle produced either u or $\dot{h}$ response). The coupling occurs both from aerodynamic aspects (i.e.,

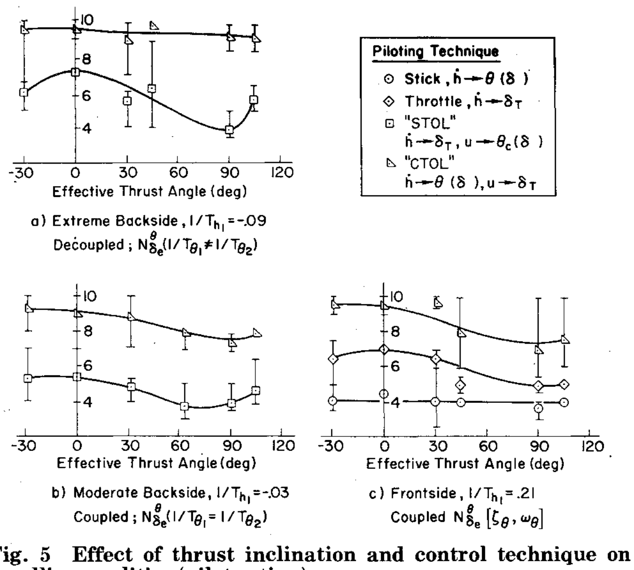

Fig. 5 Effect of thrust inclination and control technique on handling qualities (pilot rating).

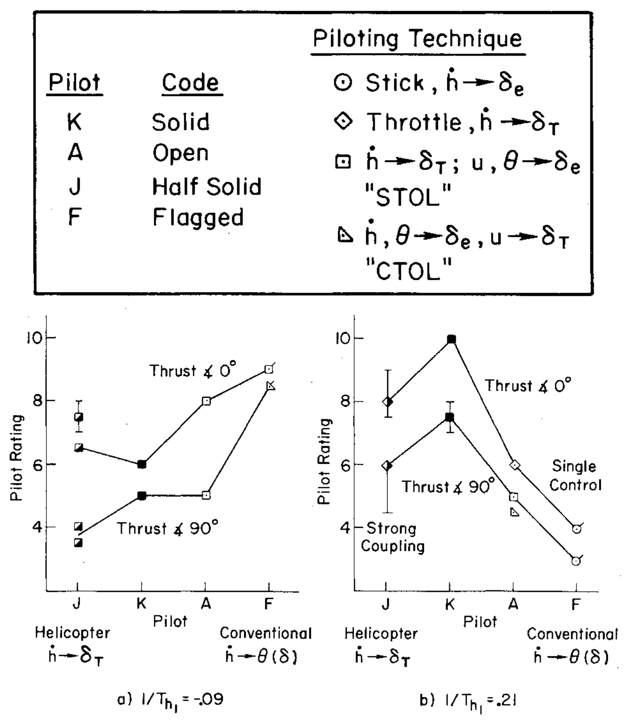

Fig. 6 Effect of flight background on ratings.

Table 1 Test configurations and range of variables[a]

Condition no.	Path mode denominator $1/T_{\theta 1}$ (ζ_θ)	Path mode denominator $1/T_{\theta 2}$ (ω_θ)	Altitude rate numerator[b] attitude $1/T_{h1}$	Altitude rate numerator[b] throttle $1/T_{h\theta}$	Speed numerator[b] attitude $1/T_{u1}$	Speed numerator[b] throttle $1/T_{u\theta}$	Throttle sensitivity $\cdot Z_{\delta T}/X_{\delta T}$ g/in.	Thrust angle arc tan $-Z_{\delta T}/X_{\delta T}$	X_w
1	0.1	0.5	−0.09	0	0.5	0.5	−0.146/−0.0363	104	0
2				0.1		NA	−0.15/0	90	
3				0.5		0.5	−0.106/0.106	45	
4				0.79			−0.075/0.13	30	
5				NA			0/0.15	0	
6				0.59			0.075/0.13	−30	
7	0.3	0.3	−0.03	0	0.73	0.9	−0.146/−0.0363	104	0.1
8				0.1		NA	−0.15/0	90	
9				0.3		0.3	−0.134/0.067	63.5	
10				0.79		0.44	−0.075/0.130	30	
11				NA		0.50	0/0.150	0	
12				−0.59		0.56	0.075/0.13	−30	
13	(0.6)	(0.5)	0.21	0	−0.86	2.5	−0.146/−0.0363	104	0.5
14				0.1		NA	−0.15/0	90	
15				0.5		0	−0.106/0.106	45	
16				0.79		0.79	−0.075/0.13	30	
17				NA		0.5	0/0.150	0	
18				−0.59		0	0.075/0.13	−30	

[a] Dynamic characteristics valid for perturbation about 60 knot trim condition.
[b] NA in the limit when either X_δ or Z_δ are zero and the time constant is undefined, i.e., for $\theta_T = 90°$, ${}^{u}N_{\delta T} = X_{\delta T}\,[s + (1/T_{u\theta})] = X_w Z_{\delta T}$; for 0°, ${}^{h}N_{\delta T} = -Z_{\delta T}[s + (1/T_{h\theta})] = -Z_u X_{\delta T}$.

through variation in X_w and Z_u terms), static control (i.e., $X_{\delta T}/Z_{\delta T}$) derivatives, and combinations of both, as illustrated in the expressions for $1/T_{u\theta}$ and $1/T_{h\theta}$ [Eqs. (4) and (5)]. The "odd" thrust inclination of 63.5 was deliberately chosen to make the $1/T_{u\theta}$ zeros cancel an appropriate pole.

As a final comment on the experimental design, note the variation evident in the values of the backside parameters, $1/T_{h1}$ (Table 1). As already observed, it is not possible to make changes in the path coupling characteristics which are independent of the backside parameter. Accordingly, the backside and coupling variation were set to oppose each other. That is, the decoupled denominator dynamics (i.e., $1/T_{\theta 2} > 1/T_{\theta 1}$ and $X_w = 0$) were tested for an extreme backside condition, $1/T_{h1} = -0.09$, and conversely, the coupled denominator was tested at an extreme frontside configuration, $1/T_{h1} = 0.21$. By this means, whether the coupling or backsidedness was governing effect could be assessed as well as the degree to which favorable thrust inclination and interaction could overcome either of these primary path control deficiencies.

Four experienced test pilots were used in the experiment. Their varied background and flight experience provides a representative sampling of piloting qualification ranging from helicopters to conventional transport. One pilot also has extensive flight experience in a deflected-slipstream-type STOL aircraft. Each pilot was given a general description of the experiment at the beginning of his participation in the program. Pilots were instructed to fly first one technique, $h \rightarrow \delta_T$ (STOL), then the other, $h \rightarrow \theta$ (CTOL); however, they were free to consider other methods of control also. The pilots were asked to comment on and separately rate, using the Cooper-Harper Scale,[10] the flying qualities associated with ILS glide path control, ILS speed control, and visual flare. An over-all rating was solicited.

Results and Discussion

The pilot ratings for each of the configurations tested are summarized in Fig. 4 as a function of thrust inclination and control technique. Both factors have significant effect on path control as evident by the rating trends. Also, static flight path stability alone (i.e., $1/T_{h1} > 0$) is not sufficient to indicate good or bad ratings. For example, good and bad ratings are evident at each of the backside levels, depending on the thrust inclination and pilot's control technique.

The rating trends indicated represent an average value with the extremes for the various pilots indicated by the range symbol, ‡. A considerable variance in rating is apparent and was undoubtedly influenced by the limited training time available to overcome the background-related biases of the subject pilots. That is, as later discussed in more detail, a given configuration was judged more harshly by those pilots unfamiliar with the particular control technique required (for best results). While increased familiarization time in the simulator would probably have produced more uniform results, there would still be some residual (statistical) scatter. As a matter of fact, a comparison of the present data trends with those from past investigations given in Ref. 11 shows that the observed data variances are not much different when only the "static" coupling parameters, $-1/T_{h1} = (g/U_0)(d\gamma/dU)$, are considered. As a general comment, the current results and those obtained from several other sources were compared in Ref. 11 and showed reasonable agreement from the standpoint of the deterioration of pilot rating with changes in the backside parameter. In effect, the current results do not contradict the findings of previous investigations relative to the significance of the backside parameter, but they do suggest that part of the variation evident in pilot opinion stems from the other factors involved. Among these are pilot preference for a given control technique which may not be the best, and configuration aspects reflected in the associated effects of thrust angle and other couplings. In fact, these, rather than backsidedness *per se*, may be the central issue in his opinion.

However, at this point it is worth noting that the so-called backside (STOL) technique is increasingly superior to the conventional control technique as $1/T_{h1}$ becomes more negative. The implication is that the throttle is then used exclusively as a means of controlling path, and that attitude is used only as necessary to regulate speed errors. In fact, some of the pilots' comments show that at these backside situations they do not attempt to control speed with the throttle as a means of stabilizing the speed divergence. Instead, they employ stable $h \rightarrow \delta_T$ and avoid the more demanding task of controlling the speed divergence associated with the backside condition. The disadvantage of using this strategy is the normally more sluggish response of flight path to throttle.

However, if we return to the specific consideration of the data relative to the predictions of Figs. 3 and 4 for the various backside situations, we find that the previous rating trends are well confirmed. In particular, the predicted pilot rating trends based on the combined effects of the closed-loop performance parameters (i.e., effective altitude bandwidth, ω_{ch} and gain, $A_{\dot{h}}$) given in Figs. 3 and 4 are essentially the same as those shown in Figs. 5a and 5b.

For example, in Figs. 5a and 5b, starting with the higher inclinations (i.e., for thrust angles between 90° and 0°), the ratings gradually degrade with decreasing thrust incidence, which was the same trend predicted in Figs. 3 and 4. Increasing the thrust angle beyond 90° produced the more rapid deterioration, as evident from Fig. 5a. The major criticism directed at this configuration was the aircraft's tendency to slow down for positive throttle inputs (e.g., when arresting sink rate). Correcting this adverse speed change required the pilot to use attitude changes which opposed the flight path corrections, and the tendency to slow down resulted in a more critical angle of attack situation. For example, to regain the speed loss resulting from a positive flight path correction requires the pilot to pitch over. This tends to increase the speed but at the same time nullifies part of the desired flight path correction and, in effect, reduced the gain as predicted in Figs. 3 and 4. This adverse interaction between flight path and speed often resulted in excessive attitude excursions and throttle motions resembling a PIO. This multiple control PIO tendency was noted most by the pilots who were less familiar with the so-called STOL technique. In summary, this condition suffered from an incorrect (sign) u response, which reduced the $h \rightarrow \delta_T$ gain, rather than from dynamic coupling which was still small.

Furthermore, for the highly-coupled situation given in Fig. 5b, only the single-loop control $[h \rightarrow \theta_\delta(s)]$ was considered nearly satisfactory by the pilots. In this case thrust inclination had little effect on the pilot control since the throttle was not used. However, when the pilots attempted to employ both controls (elevator and throttle), they had great difficulty sorting out the response effect of a given input because of the strong coupling between u and $\dot{h}$. This confusion obviously inhibited the rating discrimination for either control technique; although the STOL technique produced more consistent, although poor, rating data.

In any event, some of the pilots experienced a strong tendence to oscillate along the path using only stick; and one pilot, in particular, noted the resemblance to pilot-induced oscillations (PIO). Although he attributed these tendencies to problems with pitch attitude control, they are more accurately a reflection of the flight path control and sensitivity between flight path response and attitude. Similar problems encountered with conventional angle of attack autothrottles (which modify X_w as here) are discussed in Ref. 8. Also, the Ref. 7 PIO correlations and criteria boundaries indicate a probable "benign" PIO for the $h/\delta_e]_{\theta \rightarrow \delta_e}$ characteristics of these cases.

As a final observation on the results of this investigation, it is worth noting that these results suggest that a pilot preference for a given technique cannot be ignored and, consequently, presents a nagging question relative to STOL aircraft design. In the following, we will illustrate the apparent effects of pilot preference, using the somewhat limited results obtained in the current experiments.

As a starting point, we have ordered the abscissae of Fig. 6 according to the flight backgrounds of the participating pilots, starting at the left with helicopter-experienced pilots and proceeding right to transport or conventional aircraft pilots. In this manner we may infer to some degree the individual pilot's preferences, as exhibited by the ratings plotted for the two extreme configurations; and the influence that flight background has on ratings. The most diverse background (and skills) in the current tests are represented by Pilots J and F, respectively. Pilot J, basically a Navy-trained pilot with extensive helicopter experience and with a personal preference for the so-called backside control technique, is in direct contrast to Pilot F, a highly experienced transport pilot who prefers the CTOL technique. Further, Pilot F felt strongly that STOL aircraft should be controlled in the same manner as contemporary conventional transport aircraft (i.e., as Harris outlined, control column for flight path and throttle for speed).

Pilot K, who also is Navy trained but with limited helicopter and VTOL experience, represents an intermediate, as does Pilot A, who has a diverse background which includes fighters and STOL transport aircraft.

With this pilot background in mind, consider now the rating data shown for thrust inclinations of zero and 90° and for the two extreme dynamic configurations (i.e., backside and frontside). The symbols, and associated legend, identify the actual techniques used to obtain these "best" ratings for a given configuration and pilot. For the extreme backside situation of Fig. 6, we see that the pilots' flight backgrounds do appear to strongly influence their ratings. That is, the ratings clearly indicate a degrading trend for the pilots less experienced with the so-called STOL technique. For example, the helicopter- and Navy-experienced Pilot J ratings are always better than those for the conventional Pilot F. However, at the 0° thrust inclination even the helicopter pilot considered the thrust response sluggish and unacceptable.

Turning to the extreme frontside condition, we see essentially the reverse of the trend obtained for the backside situation. That is, the STOL pilots are now rating the system more adverse than the conventional pilots. This apparently stems from the STOL pilots' insistence on using the dual control technique, where throttle, as a primary control, is used to control $\dot{h}$ and u is controlled by attitude. However, due to the strong interaction between u and $\dot{h}$ responses to the throttle, this technique has limited effectiveness. Part of the problem is due simply to the fact that throttle is considered the primary path controller. Thus, the path and u responses to throttle must be separable to satisfy STOL pilots. This is not true for the conventional pilot, who considers the throttle more of an auxiliary control. Thus, the single $h \rightarrow \theta(\delta)$ or $h \rightarrow \delta_e$ loop (symbol Θ) with no attempt to control (the small) airspeed excursions, which is compatible with the inherent aircraft response (Fig. 2) is natural and preferred. Accordingly, when the conventional pilot discovered the suitability of flight path control with attitude (through elevator), he rated it totally satisfactory.

The major point of the foregoing is that the trends are reversed. We see, therefore, that it is difficult to dictate a single control technique which will be satisfactory for all aircraft configurations or pilots. In particular, pilots who are used to controlling flight path with throttle will, in general, tend to maintain this control technique, regardless of the aircraft's configurations and its limitations. Consequently, where aircraft-related parameters limit the ability to use the pilot's desired technique, he will (at least initially) degrade the vehicle from the standpoint of handling qualities. Therefore, we conclude that arbitrarily setting a given control technique for a particular type of vehicle may seriously limit its initial acceptance by individual pilots.

Conclusions

In general, the results of the experiment confirm that the pilot's ability to utilize either of the prevalent control techniques depends on the purity of the responses to individual controls in their assigned role. When corrupting effects are present the relative magnitude of the "secondary" responses should be small and complementary. For example, if throttle is used to increase flight path angle, the associated speed error should be small and preferably positive so that correcting it with a positive (nose up) attitude change adds to (complements) the desired increased climb.

Specific conclusions are:

1) Thrust inclination affects the boundary values of the backside parameter (i.e., $1/T_{h1}$ of $d\gamma/dU$).

2) Control technique {i.e., either CTOL [$h \rightarrow \theta(\delta_s)$; $u \rightarrow \delta_T$] or STOL [$h \rightarrow \delta_T$, $u \rightarrow \theta(\delta_s)$]} and pilot familiarity are major factors in STOL handling qualities.

3) The attitude numerator ${}^{\theta}N_{\delta e}$ factors fundamentally govern the path control response modes which are essentially independent of the short-period modes. However, the separation or coalescence of the speed and flight path responses to control inputs also depends strongly on the control force inclinations (and moments, neglected for convenience in this effort). a) Attitude factor (mode) separation is desired because, by proper selection of thrust inclination, favorable cancellation of modes and purified responses are then possible. As demonstrated by the current results, this cancellation or purification in response has a significantly favorable effect on handling qualities. b) Conversely, coupled attitude factors (modes) inherently couple both speed and flight path so that there is little possibility of cancellation by thrust inclination.

4. The pilot is restricted to single controller techniques for strongly coupled path/speed dynamics. In particular, where the coupling is due to large positive X_w as investigated here, flight path control with stick is the only satisfactory control technique. Since the pilot has no practical means of speed regulation, he has less flexibility in correcting for unusual and off-nominal situations. This implies that an autothrottle (thrust horizontal) concept based on a simple angle-of-attack feedback (i.e., $\alpha \rightarrow \delta_T$) may be unsuitable for STOL application.

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