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MAJS: /*GLIDE PATHS/*MANUAL CONTROL/*PITCH (INCLINATION)/*POWERED LIFT AIRCRAFT

SYMBOLS

AWRA	augmentor wing research aircraft
a_{x_B}	body axis longitudinal acceleration
C_j	blowing coefficient
D	aerodynamic drag
$d, \dot{d}$	glidepath deviation and rate
dlc	direct lift control
F_s	pilot's column force
g	acceleration due to gravity
ILS	instrument landing system
K_D, K_u	speed control director display gains
K_p	force gain of pitch rate command system
K_γ, K_θ	pitch flight director display gains
$K_{\Delta\gamma}$	glidepath control law gain in the pitch flight director
L	total lift
L_A	aerodynamic lift from the wing alone
L_{PL}	propulsive lift contribution to total lift
PR	pilot rating
q	pitch rate
R	slant range to touchdown
SAS	stability augmentation system
s	Laplace variable
T	engine thrust
T_h	reaction thrust component from engine hot section exhausted through rotatable nozzles
U_o	reference speed
u	perturbation longitudinal velocity
V_{CAS}	calibrated airspeed

$\bar{V}$	filtered airspeed
W	weight
X	aerodynamic force along the x stability axis
Z	aerodynamic force along the z stability axis
α	body angle of attack
γ	flightpath angle
γ_o	reference flightpath angle
$\left.\frac{d\gamma}{dV}\right\|_{ss}$	backside parameter; change of flightpath angle with airspeed with propulsion system controls fixed
ΔV	velocity error from reference approach value
$\left.\frac{\Delta\gamma}{\Delta\theta}\right\|_{ss}$	steady-state change in flightpath angle associated with a change in pitch angle
δ_{ch}	augmentor choke deflection
δ_e	elevator angle deflection
δ_{PFD}	pitch flight director signal
δ_{SCD}	speed control director signal
δ_T	throttle deflection
δ_ν	nozzle angle deflection
θ	aircraft pitch angle
θ_c	commanded aircraft pitch angle
ν_o	reference trim nozzle angle

FLIGHT EXPERIMENTS USING THE FRONT-SIDE CONTROL TECHNIQUE DURING PILOTED APPROACH AND LANDING IN A POWERED-LIFT STOL AIRCRAFT

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SUMMARY

The front-side control technique is typically not used for the operation of powered-lift aircraft because of the potential flightpath instability associated with operation on the backside of the drag curve. In addition, many aircraft designs do not possess adequate longitudinal thrust capability with sufficient authority and speed of response to provide the necessary thrust modulation. For powered-lift aircraft in which this longitudinal thrust capability is available, however, the use of an automatic speed-hold system can ensure long-term flightpath stability while providing (perhaps with artificial heave augmentation) satisfactory dynamic flightpath response to pitch attitude inputs. Equally important, the use of an automatic speed-hold system minimizes pilot workload by effectively reducing the glidepath control task to the manipulation of a single control.

If this automatic system is relied upon for routine operations, it is also important to assess the consequences of its failure. This research reviewed the essential features of flightpath control, using an automatic speed-hold system which was evaluated during previous research, and extended those studies to investigate the capability of the pilot to manually perform the speed-control task, as might be required following a system failure. To evaluate their influence on the control task, alternative cockpit controllers (proportional or rate) for manual operation of the longitudinal thrust control were assessed in conjunction with several flight director display features.

INTRODUCTION

The growing interest in powered-lift aircraft has focused attention on the development of advanced flight control systems to support their operation. From a handling point of view, the flight control challenges in the longitudinal axes stem mainly from the details involved with managing the orientation and magnitude of the thrust vector (although the reduced aerodynamic damping and the prolonged response times that are associated with the low dynamic pressures are also important considerations). Large changes in the effectiveness of pitch and throttle controls, normally used for the control of flightpath and airspeed, are typically involved in transitioning between the conventional and powered-lift flight regimes. Also, there is usually a need for some additional longitudinal control to govern the orientation of the

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thrust vector. This additional control frequently introduces a redundancy, in the number of controls available for the management of speed and flightpath, that may prove difficult for the pilot to manage, particularly during a complex task such as a decelerating approach in instrument conditions. Alternatively, this redundancy may be incorporated into some stability and control augmentation system, substantially reducing pilot workload and at the same time enhancing maneuverability. Among other factors influencing the piloting task are (1) the cross-coupled responses that may be generated through his use of controls, (2) the flightpath instability potentially associated with powered-lift operations on the backside of the drag curve, and (3) the influence of proportionally larger atmospheric disturbances stemming from the kinematics associated with low-speed steep approach operations.

Although many powered-lift aircraft have been flown that have had manageable and, in some cases, good control characteristics, the need for improved handling qualities, particularly for performing complex tasks during instrument flight, has almost always been identified. In addition, the unusually large flight envelope that is characteristic of powered-lift aircraft suggests that improved operating economics or, alternatively, enhanced military effectiveness, could be achieved with control systems that permit the pilot to rapidly configure to and from the powered-lift regime with ease. To these ends, various advanced flight control concepts have been proposed or tested, most of which take advantage of modern digital computing techniques and equipment for their implementation.

Reference 1 describes a split-axes translational motion and attitude command system for a V/STOL aircraft that was evaluated in a large moving-base simulator. The flight tests reported in reference 2 considered several control and cockpit display combinations, for decelerating approach to the hover, that were evaluated in a variable stability ducted fan V/STOL aircraft. Reference 3 details an advanced trajectory-command flight control system using a mathematical model representing the aircraft's aerodynamic and engine forces over its entire flight envelope. The model is solved inversely to yield the control deflections appropriate to the desired motion. This concept was implemented and test flown in a powered-lift jet-STOL aircraft as an automatic control system; however, it can easily be adapted as a manually controlled flightpath and speed-command system. This particular design approach seems useful for powered-lift aircraft, in which there is a significant amount of cross-coupling between the controls used to generate changes in total lift and drag forces. Reference 4 describes a similar flightpath and speed-command system that was developed for a large military jet-STOL transport aircraft; however, comprehensive flight-test data describing its performance and handling qualities are not available. In the investigations reported in references 5, 6, and 7, the fundamentals involved in a variety of glidepath control concepts applicable to powered-lift STOL aircraft operating at a fixed point on the backside of the drag curve were explored. Finally, the flight tests reported in reference 8 evaluated several STOL control concepts and associated flight directors in the more demanding context of decelerating curved approaches in simulated instrument conditions.

The objective of this investigation was to explore in greater detail the fundamental features of flightpath command and speed-hold systems associated with low-speed STOL approaches in powered-lift aircraft. For simplicity, fixed-point operation in the powered-lift approach configuration is considered rather than including transition control and configuration management.

This type of control system is frequently referred to as a front-side control system, because it permits the pilot to maintain the control technique used in conventional flight, that is, commanding flightpath changes by modulating pitch attitude.

To prevent the instability in flightpath response which would otherwise ensue because of operation on the backside of the drag curve, an automatic speed-hold feature is typically incorporated. Since this concept requires modulation of longitudinal forces with significant levels of control authority and bandwidth, it may not be applicable to all aircraft designs. Partly because of this, and because of the probable requirement for automation, the concept has not received the same level of study as the more generally applicable backside glidepath control technique, which involves modulation of propulsive-lift forces oriented nearly orthogonal to the flightpath (refs. 6, 7, and 9).

This report provides a simple theoretical framework for the front-side flightpath command and speed-hold system and reviews results from the previous flight research of references 6-8 in which some of the desirable features of these systems were identified. The particular emphasis in this investigation was on evaluating the pilot's ability to maintain the same control technique following a failure of the automatic speed-hold system, as influenced by various cockpit display and pilot controller configurations. System performance and pilot opinion data are included to support the results of these evaluations.

This research was carried out as part of a cooperative program between the United States and Canadian governments to investigate the potential of powered-lift STOL technology. The participating Canadian agency was the Flight Research Laboratory of the National Aeronautical Establishment, a division of the National Research Council of Canada. Some of the other elements of this program are described in reference 10.

DEFINITION AND PRINCIPLES OF FRONT-SIDE CONTROL

A brief summary of the principles of flightpath control for powered-lift aircraft using front-side or backside control techniques or combinations of both is presented here to clarify the details that are of interest in this flight investigation. Steady-state flight control considerations are discussed first, and then the factors affecting dynamic response are addressed.

The steady-state equations of motion in wind axes are

$$\frac{L}{W} = \cos \gamma \tag{1}$$

$$\frac{T-D}{W} = \sin \gamma \tag{2}$$

where T represents the component of thrust in the direction of flight. For many powered-lift designs, this constituent of the net longitudinal force is often not separately distinguishable from the more conventional aerodynamic drag terms, which are generally strongly influenced by the propulsion system. Similarly, the total lift force L includes the effect of the powered-lift system. For simplicity, however, lift can be considered to consist of a conventional aerodynamic component L_A from the wing alone with the powered-lift system inoperative, and an additional component L_{PL} representing the increment in lift arising from operation of the powered-lift system.

It is assumed that separate and nearly uncoupled control over the longitudinal and normal components of the propulsion system forces is provided. This separation is difficult to provide in practice, but once the powered-lift configuration has been achieved, comparatively small amounts of relatively pure longitudinal control power (< 0.1 g) can be provided by simply vectoring the nearly normally oriented propulsive force vector over small angles about the trim setting. Examples include flap modulation about a nominal deployed position (upper-surface-blown or externally-blown powered-lift concepts), or nozzle-angle modulation about the deflected thrust position (augmentor wing or direct vectored-thrust concepts). The normal component of the propulsion system forces is controlled by changing the engine throttle setting or operating point, an action usually having a small though often noticeable effect on the longitudinal thrust component.

The significance of equations (1) and (2) derives from their emphasizing the point that long-term changes in flightpath angle can be effected only through a change in the net longitudinal force balance. Changes in lift, although influencing the transient response, have only a secondary effect on the long-term response. The front-side and backside control techniques will be differentiated on the basis of how these changes in longitudinal force are accomplished.

Because landing field length considerations generally constrain the pilot from effecting significant changes in airspeed during approach, using airspeed for drag modulation and hence flightpath control is ruled out; instead, some active modulation of the powerplant forces is used. For the case in which modulation of the propulsion system or other force-producing device causes only changes in forces that are essentially aligned with the flightpath (as in a conventional aircraft), the longitudinal force balance necessary for sustained changes in flightpath angle that is prescribed in equation (2) is accomplished directly. In addition, the constant-speed constraint mentioned previously results in the need to adjust pitch attitude in a manner prescribed by the following perturbation equation (justified later) that describes the difference in the state variables between two neighboring steady flight conditions:

$$\left.\frac{\Delta\gamma}{\Delta\theta}\right|_{ss} \doteq 1 , \qquad \left.\frac{\Delta\alpha}{\Delta\theta}\right|_{ss} \doteq 0 \tag{3}$$

It is this relationship between a change in pitch attitude and the ensuing change in flightpath angle that results in the flightpath command and speed-hold terminology used in this discussion. In fact, the preferred way to view the use of the two controls, θ_c and T, that are involved in this control technique is that glidepath changes are made with attitude, followed by thrust to maintain speed, an interpretation that will be justified later when the dynamic response considerations are addressed. Since this glidepath control mechanism is identical in the long term to that used for conventional aircraft having a thrust vector oriented nearly in the direction of flight and operating (usually) on the front-side of the drag curve, the technique is referred to as the front-side control technique. To summarize, the essential features of front-side control for purposes of this study involve modulation of pitch attitude for glidepath control (also having short-term dynamic response implications to be discussed later), and an associated modulation of propulsion system forces oriented nearly in the direction of flight for the purpose of speed control.

The front-side control technique is usually not used for glidepath control in powered-lift aircraft because not every aircraft design permits the rather large control authority and wide bandwidth in longtudinal force modulation that is necessary to allow the required range in glidepath control. In this regard, reference 9 suggests ±4° as the amount of control necessary on either side of the nominal descent path to accomplish satisfactory tracking in rough air conditions. This corresponds to a significant ±0.07 g specific force requirement that is generally not easily available in powered-lift aircraft whose principal feature in the approach configuration is a normally-inclined thrust vector. In addition to these considerations, there is the equally or even more important flightpath instability potentially associated with the usual operation of powered-lift aircraft on the backside of the drag curve; this latter instability is caused by the high induced drag of these aircraft in the low-speed approach configuration. This instability is exemplified in figure 1(a), where it is seen that failure to add the necessary longitudinal thrust when pitching up to regain the path from below results, in the long term, in a steeper glidepath. On the other hand, adding longitudinal thrust to maintain speed exactly, prevents this reversal and results in the desirable flightpath response shown in figure 1(b). A further deterrent to the use of the front-side technique, at least for manual control, is the typically similar frequencies of control activity that are involved in the use of throttle and pitch attitude. This is unlike conventional aircraft, in which there is significant frequency separation, and has led to the conclusion advanced in reference 9 that such concepts likely involve too high a workload for routine instrument approach operations. Consequently, the normal implementation of these systems is with an automatic speed-hold system that ensures the potential flightpath instability of the backsidedness cannot develop.

The backside control technique involves modulation of the component of lift obtained from the propulsion system, which is oriented orthogonally to the flightpath, subject in the long term to the constraint

$$L_A + L_{PL} = W \cos \gamma \doteq W \tag{4}$$

A reduction in throttle setting, for example, reduces the amount of powered-lift, hence requiring an increase in wing-generated aerodynamic lift. This is accomplished primarily through an increase in angle of attack. Flightpath control is then realized indirectly through changes in the amount of induced drag associated with this process, in accordance with equation (2). If speed is also to be maintained constant, small adjustments in the new angle of attack and hence in the aerodynamic drag will in general be necessary through the use of small changes in pitch attitude. As discussed in references 5 and 6, the details associated with the long-term use of pitch attitude to control speed have a significant influence on handling qualities.

Alternatively, use may be made of any other secondary control to automatically modulate longitudinal forces over a fairly small range as necessary to maintain speed, while changes in throttle setting indirectly command the large aerodynamic drag changes necessary for glidepath control. This allows pitch attitude to remain exactly unchanged between any two neighboring steady flight conditions, resulting in a significant improvement in handling qualities. These considerations, which are discussed in greater detail in references 7 and 8, constitute refinements to the backside control technique.

In summary, the backside technique involves flightpath control achieved primarily through throttle-induced changes in angle of attack, with little change in attitude except as necessary to maintain speed

$$\left.\frac{\Delta\gamma}{\Delta\alpha}\right|_{ss} \doteq 1\,, \qquad \left.\frac{\Delta\theta}{\Delta\alpha}\right|_{ss} \doteq 0 \tag{5}$$

The idealized front-side and backside control techniques just described involve separate modulation of nearly orthogonal propulsion system forces oriented nearly along or nearly normal to the flightpath. Although the discussion and the pilot control technique are simplified considerably in this way, such a pure separation of the effects of changes in the propulsion system controls does not usually exist. Frequently, modulation of the control affecting longitudinal force also adversely affects the propulsive lift to some degree resulting in a depletion in the steady-state gain of the flightpath command and speed-hold system. That is, for the front-side technique,

$$\left.\frac{\Delta\gamma}{\Delta\theta}\right|_{ss} < 1\,, \qquad \left.\frac{\Delta\alpha}{\Delta\theta}\right|_{ss} > 0$$

reflecting the increment in aerodynamic lift that needs to be supplied by the wing to offset the net loss in powered lift owing to the coupled operation of the longitudinal propulsion system control. As an example, this effect is shown for the case of a vectoring nozzle system in figure 2. Of course, the powered lift can be restored to its nominal value by adjusting the throttle. This complicates the control task, however, because three controls - pitch attitude and the longitudinal and normal propulsion system controls - are now involved.

More usefully, additional powered lift can be used to increase the steady-state flightpath-command gain to values greater than unity. Reference 7 evaluated the essential features of a control augmentation system that used the three controls mentioned above to provide a gain of

$$\left.\frac{\Delta\gamma}{\Delta\theta}\right|_{ss} \doteq 1.3\;; \qquad \frac{\Delta\alpha}{\Delta\theta} \doteq -0.3 \tag{6}$$

This system received excellent pilot ratings for glidepath tracking, largely on account of the reduced pitch activity needed to accomplish satisfactory glidepath tracking. Although the flightpath-command concepts described in references 3 and 4 can also incorporate this feature in a fairly simple manner, it is the use of nearly pure longitudinal force modulation and the resulting unity gain flightpath-command system that is considered for the front-side control evaluations reported here. Simplifying the scope of this investigation in this way reflected (1) the unique capability of the test aircraft used for these evaluations, in which there was ample longitudinal force authority and bandwidth that was largely independent of the powered-lift component, and (2) the desire to consider realistic manual control modes (involving only two controls) that might be feasible following a failure in the automatic speed-hold system. To allow consideration of these principles in more concrete terms, the relevant design features of the test aircraft used in this investigation are provided next.

AIRCRAFT DESCRIPTION

Propulsion System Design

The Augmentor Wing Research Aircraft (AWRA) is a modified De Havilland of Canada DHC-5 Buffalo (fig. 3) which is equipped with an augmentor flap (fig. 4). The four-segment flap is blown internally by the cold bypass flow from two Rolls Royce Spey 801-SF engines. This cold flow is cross-ducted to minimize lateral and directional transients in the event of an engine failure. The residual hot thrust from each engine (approximately 60% of the total) is exhausted through rotatable nozzles.

In the approach configuration, the setting of the engine throttle controls the magnitude of the flap-deflected cold thrust and nozzle-vectored hot thrust. The direction of the latter can be independently vectored between 6° and 104° relative to aircraft datum. Typically, the nozzles are deployed to a setting near 75° for steep descent in order to provide both additional drag and powered lift in the approach configuration. As suggested in figure 2, modulation of nozzle angle in the region between about 45° and 104° provides independent longitudinal force control while also contributing an approximately constant amount of powered lift separate from that furnished by the augmentor flap. Provision exists for a modest amount of direct-lift-control (dlc) through symmetric actuation of electrohydraulic choking surfaces designed as part of the inboard augmentor flap segments; however, the pilot has no direct control over this function. Figure 5 illustrates the pilot's overhead cockpit control layout normally used for propulsion system management. The aerodynamic characteristics of the aircraft are discussed in greater detail in reference 11.

Basic Angular Stability Augmentation System (SAS)

Limited-authority electrohydraulic actuators are incorporated in series with the pilot's pitch, roll, and yaw controls. These actuators are driven by the attitude SAS to provide rate-command, attitude-hold characteristics in pitch and roll, and rate-damping and turn-coordination characteristics in yaw. This SAS mode is available for use at speeds below 140 knots, although the requirement for its use is only significant in the approach configuration at speeds below 90 knots. A trim follow-up circuit in pitch slowly repositions the pilot's control to restore the full authority of the series pitch actuator.

The pitch-attitude SAS in particular is a useful workload-reducing feature which is gaining wide acceptance for this class of aircraft. Often the need for such a system derives not only from the low stability inherent in low-speed flight, but also from significant variations in the aerodynamic center of pressure or from induced-flow effects at the tailplane. These center-of-pressure variations and flow effects may occur either during transition to powered lift or while modulating the propulsive-lift controls used for longitudinal path control in the approach configuration. Such difficulties are minimized in the AWRA, however, with the T-tail arrangement and the high degree of center-of-pressure stabilization effected by the internally-blown augmentor flap. In addition, the thrust lines of the vectorable hot-thrust nozzles are located close to the aircraft center-of-gravity range; thus pitching-moment changes arising from their sometimes aggressive and rapid use are minimized. Details describing the rate-command attitude-hold SAS are provided in reference 7.

Performance Envelope: Descent Configuration

Data describing the trim control positions for this aircraft in the descent configuration without any form of speed-hold augmentation are shown in figure 6 for a fixed nozzle and a fixed throttle. In each case, a substantial amount of flightpath authority is available over the useful range of operation of the variable propulsion-system control, either throttle or nozzle. In the case of the backside control technique (fig. 6(a)), angle-of-attack changes are involved that are nearly equivalent to the flightpath changes caused by changing throttle settings, if speed is held constant. On the other hand, constant speed operation about the operating point using nozzle modulation (fig. 6(b)) is accomplished with nearly constant angle of attack; hence the changes in pitch attitude are nearly the same as the resulting changes in flightpath angle. The rounding of the angle-of-attack contours in the upper portion of the envelope is caused primarily by the loss in the hot-thrust component of lift as the nozzles are retracted to their "up" position; for example, during the course of a large upward correction. This lift loss is manifested as a reduction in the steady-state flightpath angle response to pitch-attitude control, since with constant speed this lift can only be furnished through an increment in the angle of attack. In fact, the inboard augmentor chokes were used to reduce this undesirable effect, as will be described later.

As discussed in greater detail in reference 8, the particular position chosen for the fixed or trim control is also an important consideration in the operation of powered-lift aircraft. Not only must there be an adequate range of authority available to carry out sustained corrections on either side of the nominal aerodynamic flightpath (i.e., the inertial glide slope adjusted for the winds of the day), but efficient operating points must be chosen that optimize the sharing between aerodynamic and propulsive lift. In addition, aerodynamic safety margins must be preserved by preventing excessive deviations in airspeed or angle of attack.

EQUATIONS OF MOTION AND DYNAMIC RESPONSE

This section is devoted to the development of a simplified theoretical framework that provides insight into the effect of nozzle, or longitudinal thrust, modulation, emphasizing its similarity to simple thrust modulation in a conventional aircraft.

The small perturbation linearized equations of motion used for this analysis are (in stability axes)

$$\begin{bmatrix} s-X_u & -X_\alpha & 0 \\ -Z_u & U_o s-Z_\alpha & 0 \\ 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} u \\ \alpha \\ \gamma \end{bmatrix} = \begin{bmatrix} -g \cos \gamma_o & X_{\delta_T} & X_{\delta_\nu} \\ U_o s-g \sin \gamma_o & Z_{\delta_T} & Z_{\delta_\nu} \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \theta_c \\ \delta_T \\ \delta_\nu \end{bmatrix} \tag{7}$$

and are the same as those employed in the detailed analysis of backside control given in reference 5.

In addition to the standard assumptions associated with linearization of the general equations of motion and isolation of the longitudinal modes (ref. 12), it is assumed that (1) the stability derivatives Z_{δ_e}, X_{δ_e}, $Z_{\dot{\alpha}}$, $X_{\dot{\alpha}}$, Z_q, and X_q are insignificant in the analysis, and (2) a separate high-gain attitude-control loop allows elimination of the pitching-moment equation and substitution of θ_c for the pilot's pitch-axis control input. The analytical justification for the latter simplification is provided in reference 5. For the rate-command attitude-hold pitch SAS that was used in this investigation, the additional relationship between the pilot's actual column force input F_s and the resulting θ_c is simplified to

$$F_s = K_p s \theta_c \tag{8}$$

The control vector also contains two separate propulsion-system controls, throttle setting δ_T and nozzle angle δ_ν, which influence primarily the normal and longitudinal propulsive forces, respectively. However, provision is included for cross-coupling terms as shown. Three reference flight conditions are considered: the same nominal case as that used for the more extensive analyses in reference 5 (U_o = 60 knots), a flight condition using improved aerodynamic and engine data better reflecting the test configurations used in this flight investigation (U_o = 69 knots), and a higher speed flight condition on the front side of the drag curve (U_o = 85 knots). The stability derivatives associated with these reference flight conditions are summarized in table 1.

Imposing the constraints of constant speed and of fixed position of the propulsion system control (throttle setting) governing the magnitude of the powered-lift component, an idealized front-side control system can be characterized by

$$\begin{bmatrix} -X_\alpha & 0 & -X_{\delta_\nu} \\ U_o s - Z_\alpha & 0 & -Z_{\delta_\nu} \\ 1 & 1 & 0 \end{bmatrix} \begin{bmatrix} \alpha \\ \gamma \\ \delta_\nu \end{bmatrix} = \begin{bmatrix} -g \cos \gamma_o \\ U_o s - g \sin \gamma_o \\ 1 \end{bmatrix} \theta_c \tag{9}$$

The nozzle control has been located in the state vector because of the dependency of nozzle position on pitch attitude that is involved in the flightpath-command, automatic speed-hold control system. The transfer function describing the flightpath angle response to pitch command is

$$\frac{\gamma}{\theta_c} = \frac{1 - \dfrac{g \sin \gamma_o}{Z_\alpha} - \dfrac{X_\alpha}{Z_\alpha} \dfrac{Z_{\delta_\nu}}{X_{\delta_\nu}} \left(\dfrac{1 - g \cos \gamma_o}{X_\alpha} \right)}{- \dfrac{U_o s}{Z_\alpha} + 1 - \dfrac{X_\alpha}{Z_\alpha} \dfrac{Z_{\delta_\nu}}{X_{\delta_\nu}}} \tag{10}$$

and the corresponding angle of attack response is

$$\frac{\alpha}{\theta_c} = 1 - \frac{\gamma}{\theta_c}$$

The change in the longitudinal force control (nozzle angle) required to maintain speed precisely in the presence of short- and long-term attitude changes is

$$\frac{\delta_\nu}{\theta_c} = \frac{\dfrac{U_o}{X_{\delta_\nu}} \dfrac{X_\alpha}{Z_\alpha} \left(1 - \dfrac{g \cos \gamma_o}{X_\alpha} \right) s - \dfrac{g \sin \gamma_o}{X_{\delta_\nu}} \dfrac{X_\alpha}{Z_\alpha} + \dfrac{g \cos \gamma_o}{X_{\delta_\nu}}}{\dfrac{U_o s}{-Z_\alpha} + 1 - \dfrac{X_\alpha}{Z_\alpha} \dfrac{Z_{\delta_\nu}}{X_{\delta_\nu}}} \tag{11}$$

For the special case of pure longitudinal force control that has no cross-coupling with lift, that is, $Z_{\delta_\nu} = 0$, or approximately so, where

$$\left| \frac{X_\alpha}{Z_\alpha} \frac{Z_{\delta_\nu}}{X_{\delta_\nu}} \right| << 1 \tag{12}$$

then a simpler form is obtained

$$\frac{\gamma}{\theta_c} = \frac{1 - \dfrac{g \sin \gamma_o}{Z_\alpha}}{\dfrac{U_o s}{-Z_\alpha} + 1} \tag{13}$$

A similar simplification can be made in equation (11). This simplification provides an adequate description of the flightpath and speed-hold considerations for the AWRA when the trim nozzle angle is near 90°. The effects of lesser trim nozzle angles for which $Z_{\delta_\nu} \neq 0$ will be considered subsequently.

Flightpath Response Characteristics

Of particular significance is the first-order nature of the flightpath response to pitch control inputs, with a time-constant reflecting the damping in heave of the aircraft. The near-unity steady-state gain of the flightpath-command speed-hold system, which was referred to earlier in equation (3), is the maximum that can be achieved without also increasing the level of powered lift through increased throttle or other means to effect, for example, a reduction in angle of attack during positive (upward) changes in flightpath angle. The effect of positive or negative contributions to lift owing to modulation of the longitudinal force control δ_ν is considered in a subsequent section.

The direct effect of heave damping on the time-constant characterizing the response time of the flightpath-command and speed-hold system suggests that artificially augmenting this parameter would result in quickened flightpath response and improved handling qualities. Increasing this flightpath response time constant to values more characteristic of conventional aircraft would serve to reduce the level of pitch control activity involved in tracking glidepath, at least in the short term. Modulating the chokes located within the inboard segments of the augmentor flap about an intermediate position is a means for providing direct-lift control for this purpose. A possible mechanization to provide the additional lift would be

$$\frac{\Delta Z_\alpha}{U_o} \Delta\alpha = \frac{Z_{\delta_{ch}}}{U_o} \left(\frac{\Delta\delta_{ch}}{\Delta\alpha} \right) \Delta\alpha \tag{14}$$

where the amount of choke control commanded by the augmentation system $(\Delta\delta_{ch}/\Delta\alpha)$ might be based on using ±0.06 g of the authority available for $\Delta\alpha$ changes of ±4°. With these assumptions, $\Delta Z_\alpha/U_o = -0.27 \text{ sec}^{-1}$.

Alternatively, since

$$\frac{\alpha}{\theta_c} \doteq \frac{s}{s-(Z_\alpha+\Delta Z_\alpha)/U_o} \qquad (15)$$

a simpler implementation employing washed-out pitch attitude ensures that the authority of the dlc device will always be preserved in the long term without being affected by any changes that may occur in trim angle of attack. This has the desirable features of eliminating complications resulting from any changes in operating point or throttle setting, while also providing response augmentation to pilot-generated inputs without increasing the response to vertical gusts. This implementation was used in the speed-hold system used in this investigation, which is described in a following section.

Use of Nozzle Control to Maintain Speed

Although the expressions (11) and (13) also represent the essentials of flightpath control for conventional aircraft at constant speed, the dynamic response associated with the high induced drag and the low-speed kinematics of powered-lift aircraft result in quite different control requirements. On the premise, justified on the basis of similar ground closure rates, that the pilot will act to correct height errors from glide slope in the same time intervals that he may be accustomed to in higher-speed conventional aircraft, the flightpath-angle changes and associated pitch attitude changes involved at the lower speeds and on the steeper glidepaths characteristic of STOL operations are roughly doubled. This in itself is a significant consideration from the points of view of pilot control and passenger comfort. Moreover, the characteristic response times of flightpath-angle change to pitch are more sluggish because of reduced aerodynamic damping at low dynamic pressures, creating the need for response augmentation as described previously. The corresponding large transient variations in angle of attack and the high levels of induced drag that are associated with the dynamic use of pitch attitude result in the need to more quickly adjust the longitudinal force control than is necessary in conventional aircraft, in order to prevent changes in speed. The importance attached to controlling speed disturbances caused by maneuvering, by atmospheric turbulence, or by shears is primarily influenced by the effect these speed disturbances may have on flightpath control. (Additional considerations influencing the acceptable bounds of speed errors are their effect on aerodynamic safety margins and on landing performance.) The influence of poor speed control on the control of flightpath will be discussed briefly in terms of the degree of backsidedness (long-term considerations) and the shorter term dynamic response characteristics.

The degree of backsidedness is likely to strongly influence the acceptability or unacceptability of manual speed control used in conjunction with the front-side control technique. Even if the backside control technique is employed, operating points that are far on the backside of the drag curve may require the routine use of an automatic speed-hold system to ensure safe operation, particularly if adverse control cross-couplings were to otherwise cause significant disturbances.

A more precise definition of backsidedness, obtained from equation (7), is usually simplified to (for small γ_o)

$$\left(\frac{d\gamma}{dV}\bigg|_{ss}\right)_{\delta_T,\delta_\nu \text{ constant}} \doteq \frac{1}{g}\left[X_u + \frac{Z_u}{Z_\alpha}(g - X_a)\right]$$

giving values between 0.16 and -0.03° per knot for the three different reference flight conditions summarized in table 1. This parameter is readily interpreted as the local slope of the trim approach curves of figure 6, and reflects the deviations in flightpath angle that will develop should the pilot be inattentive to speed control. In practice, the flightpath deviations attributable to this effect usually are translated into consuming some of the available authority of the other control used to manage flightpath, a condition that persists until the speed error is corrected.

The degree of backsidedness encountered in this investigation was not severe, falling in a region determined during the research of reference 13 to have little influence on the pilot rating, at least when encountered in conjunction with the backside control technique. Similarly (and under the same conditions of backside control), reference 6 reports no particular problem with backsidedness in the same range, as long as adequate flightpath control authority was available to overcome its effects. Nevertheless, gross abuses in speed control, which undeniably are a possibility in the context of this investigation, could be expected to be cause for significant concern, and variation in the backsidedness parameter may be worthy of more detailed investigation.

The dynamic response of the ideal speed-hold system, characterized by the flightpath response and the nozzle activity required, is compared in figure 7 with the nozzle-fixed abuse case, which allows a speed error to develop. A representative pitch attitude change of 5° over 2 sec is used for the control input commanding the flightpath-angle change. The requirement for simultaneous nozzle control inputs to maintain speed, shown in figure 7(a), demand an increment in pilot workload, if accomplished manually, which according to reference 9 is considered to be unsatisfactory for routine instrument approach operations. On the other hand, the immediate speed decay and associated flightpath-angle overshoot (resulting ultimately in a reversal if $d\gamma/dV > 0$) that develops if no action is taken (fig. 7(b)) dictate the requirement to achieve some satisfactory level of speed control in order to allow adequate flightpath control. The requirement for an automatic speed-hold system is based on this need to provide satisfactory flightpath control at acceptable levels of pilot workload. Also shown in figure 7 is the effect of the heave damping augmentation described in the preceding section.

Effects of Adverse Lift Coupling

This discussion has been limited to those aircraft that have a significant amount (defined arbitrarily as ±0.07 g) of longitudinal force control, uncoupled with lift, which can be modulated at frequencies characteristic of the pilot's glidepath control task. However, such purity of control is seldom available. Typically, an increase in the longitudinal force necessary to support any moderately large upward correction to glidepath also causes a reduction in the contribution to lift provided by the propulsion system which must be restored through an increase in angle of attack, hence depleting the glidepath response. The steady-state and dynamic effects of this adverse lift coupling are best described with reference to a specific design. The case of the AWRA is considered for large changes in nozzle angle or, alternatively, for small perturbations about a reference flight condition for which the trim nozzle angle differs significantly from 90°.

When the aerodynamic interference effects of the vectored hot thrust (which may in fact be favorable) are neglected, the changes in the nozzle derivatives for a different trim nozzle angle ν_0 measured from the X-body axis are

$$X_{\delta_\nu} = -\frac{T_h}{W}\sin\nu_o$$

$$Z_{\delta_\nu} = -\frac{T_h}{W}\cos\nu_o$$

If it is further assumed that the trim nozzle angle can be widely adjusted without significantly affecting the other aerodynamic stability derivatives (power remaining fixed), then equations (10) and (11), along with the stability derivatives of table 1, can be used to demonstrate, in an approximate way, the effects of lift coupling caused by large perturbations in nozzle angle or, equivalently, modulation about a reference flight condition for which the trim nozzle angle is other than 90°.

The steady-state gain of path response to pitch attitude becomes

$$\left.\frac{\Delta\gamma}{\Delta\theta_c}\right|_{ss} = \frac{1 - \dfrac{g\sin\gamma_o}{Z_\alpha} - \dfrac{X_\alpha}{Z_\alpha\tan\nu_o}\left(1 - \dfrac{g\cos\gamma_o}{X_\alpha}\right)}{1 - \dfrac{X_\alpha}{Z_\alpha\tan\nu_o}} = F(\gamma_o,\nu_o) \qquad (16)$$

The functional dependence of this expression, which derives from linear small perturbation analysis, is explicit for γ_o, ν_o, but the implicit dependence of the derivatives X_α, Z_α, on α_o will be ignored since the differences in α_o between successive trim states will be small. Similarly, equation (11) can be written in functional form

$$\left.\frac{\Delta\delta_\nu}{\Delta\theta_c}\right|_{ss} = G(\gamma_o,\nu_o) \qquad (17)$$

so that the effect of large perturbations can be iterated in the following stepwise linear fashion

$$\left.\begin{aligned} \gamma_{i+1} &= \gamma_o + \sum_o^i F(\gamma_i,\nu_i)\Delta\theta_{c_i} \\ \theta_{c_{i+1}} &= \theta_{c_o} + \sum_o^i \Delta\theta_{c_i} \\ \nu_{i+1} &= \nu_o + \sum_o^i G(\gamma_i,\nu_i)\Delta\theta_{c_i} \end{aligned}\right\} \qquad (18)$$

The reduction in steady-state gain with a lesser trim nozzle angle, which is apparent in equation (16), and the iteratively integrated path response to a large input of θ_c are shown in figure 8. Clearly, the reduction in the normal component of hot thrust, $Z_{\delta_\nu}(\nu_o)\delta_\nu$ (and the change in the component of the gravity force along the Z-body axis) must be compensated by an increase in angle of attack to produce an offsetting force $Z_\alpha\alpha$. The trim map of figure 6, of course, reflects the general nature of these characteristics, although the precise aerodynamic and engine model used in the development of the trim-map data and the stability derivatives of table 1 differ somewhat.

The time-constant involved in achieving these reduced levels of flightpath gain to pitch input is relatively improved as a result of this adverse coupling, as indicated in figure 9(a), which was prepared directly from equation (10). It is unlikely that this provides any benefit in control, however, since the initial response is not improved, and a relatively large increment in angle of attack and hence attitude is necessary in order to achieve what is ultimately a lesser path response. The reduced steady-state gain appears to be instrumental in forcing an undesirable increase in pitch control activity in the short and the long term. This is reflected in figure 9(b), which shows the responses in angle of attack and flightpath angle for small theoretical step changes in pitch attitude for trim nozzle angles of 90° and 65°.

To reduce these adverse effects of lift coupling in the flightpath-command and speed-hold system, a compensating crossfeed between nozzle angle and the dlc chokes could be incorporated to extend the range of relatively pure longitudinal force control, thereby preserving the near-unity steady-state gain. If a choke authority of -0.1 g were dedicated for this function, lift-coupling compensation could be implemented for nozzle angles as low as 48° for the 60-knot trim conditions specified in table 1. This feature was incorporated in the longitudinal force modulation systems that were evaluated during this investigation, with the result that adverse lift coupling arising from modulation of the longitudinal force device was not found to be a problem, except for extreme corrections toward level flight.

MECHANIZATION OF AUTOMATIC AND MANUAL FRONT-SIDE CONTROL SYSTEMS

Research Avionics System

The AWRA is equipped with a comprehensive and flexible digital avionics research system referred to as STOLAND. STOLAND provides the primary functions of navigation, guidance, control (via flight director or automatic servos), display generation, and system management. The system is shown schematically in figure 10. Its features were used to mechanize the automatic and manual flightpath-command and speed-hold systems, which were evaluated in this investigation and which are described in this section.

A laboratory fixed-base simulation facility provided the means for software development and verification; it was also used for pilot familiarization and preliminary evaluation. Only those hardware and software details that are of concern to these tests will be described here. A more comprehensive description of the system is available in reference 14.

Automatic Speed-Hold System

Contrary to the ideal nature of the speed-hold system assumed for the preceding analysis, the implementation of any practical system needs to consider realities that are associated with control and servo system rate and authority limitations, feedback signal processing, the effects of atmospheric disturbances, and control cross-couplings. In addition, there are operational considerations pertaining to engagement procedures, methods for effecting a change in the reference speed being flown, and choice of an appropriate trim setting of the redundant longitudinal control (in this case, the throttle). The automatic speed-hold system which was developed for the curved decelerating approach investigation of reference 8 accommodated these considerations and was employed here as the basis for this more extensive evaluation. The pertinent details of the system, shown in figure 11, are documented in greater detail here.

The loop structure used in the design of the speed-control SAS includes a direct feed-forward from pitch attitude to nozzle angle in order to immediately compensate for changes in the component of gravity along the flightpath. This structure assists with the higher-frequency loop performance resulting from occasionally aggressive pitch-attitude maneuvering, and reduces substantially the gain which would otherwise be required in the velocity feedback loop. The velocity feedback loop provides gust and shear protection, ensures following of the slewing reference whenever the reference speed is changed, and compensates for minor inadequacies associated with the pitch maneuvering term. A second-order, 0.25-rad/sec complementary filter, which rejects turbulence but retains the higher-frequency inertial response, is used on the airspeed feedback quantity. It further leads to good bandwidth in response to maneuver-generated inputs, without excessive or objectionable nozzle activity arising from atmospheric disturbances. An integrator is included to prevent velocity standoff errors. The response of the system to step-like inputs in pitch attitude is shown in figure 12. These records were obtained in the simulation facility mentioned previously.

The lift-coupling compensation feature shown in figure 11 as a crossfeed from nozzle position is also designed to maintain the trim choke position at a nominal 30% of full closure for any specified reference nozzle setting. (The reference nozzle setting is determined by the trim throttle setting used for approach, which in turn is set by the pilot to establish the nominal approach angle of attack. A method to deal rationally in an operational context with the influence of wind, approach airspeed, and weight on the choice and maintenance of an appropriate throttle setting is described in reference 8.) The result of this mechanization was to allow steady-state $\Delta\gamma/\Delta\theta_c$ ratios of approximately 1.0 to be achieved for excursions in flightpath angle of ±4° about the nominal operating point, hence allowing any adverse lift-coupling effects associated with nozzle modulation to be ignored. (The simulator mechanization yielded $\Delta\gamma/\Delta\theta_c$ gains somewhat in excess of 1.0 because of an unrealistically high choke effectiveness.)

The essential performance characteristics of this flightpath-command and speed-hold system in the frequency domain are summarized in figure 13, which illustrates the responses of speed error, flightpath angle, and nozzle angle and dlc chokes to pitch control inputs in the frequency range of control. The characteristics were calculated from an analysis of the system shown in figure 11, using equations (7) and the 60-knot aircraft data from table 1. The choke effectiveness, $Z_{\delta_{ch}}$, was conservatively estimated at 0.02 m/sec^2/percent closure. Instead of modeling the lift-decoupling crossfeed from nozzles to chokes, Z_{δ_ν} was simply assumed to be zero. The nozzle servo dynamics and nonlinearities associated with the electric servo rate limit (corresponding to 20°/sec of nozzle rotation), as well as hysteresis in the mechanical nozzle drive system, were also ignored. Of significance in figure 13 are (1) the relatively good suppression of speed error over the frequency range (the amplitude ratio u/θ_c at the peak is only 0.28 knots/deg); (2) the nearly first-order flightpath response resulting; and (3) the consistent simple-gain character of the nozzle behavior. The last feature simplifies the pilot's monitoring of the system in response to his maneuver (pitch attitude) commands, and reflects the nearly direct gearing that would be manually required in the event of a failure of the automatic closed-loop system.

Configuration for Manual Speed Control

The characteristics of flightpath control using the front-side technique in association with an automatic speed-hold system had been evaluated during the course of the flight investigations reported in references 7 and 8 (the latter investigation using the system just described). Although the manual control considerations were not thoroughly addressed, the results of these tests (to be reviewed in a following section) indicated that an automatic speed-hold system was probably needed in order to eliminate the additional workload associated with the requirement for nearly simultaneous pitch and nozzle control inputs, as well as to provide the necessary safeguard for avoiding the flightpath instability associated with the backside operation. This investigation examined more closely the ability of the pilot to perform the speed-control task manually, as might be required following a failure in the automatic system.

The interest in this manual control task was also based on a proposed propulsion system design for a new-technology augmentor wing aircraft (ref. 15) incorporating a geared variable-pitch fan for longitudinal thrust control in place of the rotatable nozzles of the AWRA. This "three-stream" engine configuration, shown in figure 14 and described in more detail in reference 16, has the potential for producing a wide range of longitudinal force control without significantly affecting lift. Alternatively, the possibility of employing this manual front-side control technique could apply to any STOL or V/STOL aircraft having a mixed propulsion system design with separate control over nearly orthogonal and uncoupled components of powerplant-generated forces. To allow consideration of these more general configurations, the manual control task evaluated in this investigation considered the situation in which the pilot was required to modulate the longitudinal force control, following, for example, a passive failure in its automatic servo system. The interconnect feature between nozzle angle and choke positions, which served to eliminate any adverse lift-coupling caused by nozzle retraction, was retained in order to simulate this three-stream engine or a mixed propulsion system configuration, hence essentially removing from consideration any coupling effects with lift. Under the conditions of the failure that was assumed, the pilot was required to modulate the longitudinal control force, a function formerly carried out by the servo.

An important consideration in the fully manual operation of these propulsive-lift systems is the physical means provided to the pilot in the cockpit for exercising control over the separate components of propulsive force. To evaluate various alternatives for integrating these propulsion system controls, the electric power lever arrangement shown in figure 15 was used. Several configurations in which either proportional or rate control of the longitudinal or normal propulsion system forces was considered were evaluated; they are summarized in table 2. Although it seems clearly desirable to provide the pilot with proportional control over the full range of both propulsion system controls (e.g., throttle setting and nozzle angle or variable-pitch fan-blade angle), this is a difficult human factors design problem, and the electric controller did not provide this flexibility. Instead, the overhead throttle and nozzle controls shown in figure 5 were used to evaluate the use of two separate proportional controls that were not integrated in a single control handle. Some of the considerations involved in the use of the various controller configurations are discussed in the subsequent sections. In addition, it should be pointed out that the bandwidth of control available from the electric power lever, when connected to the aircraft throttle and nozzle controls via their respective electric servos, did not permit proper evaluation of situations involving the need for rapid and precise control inputs, such as during flare and landing.

Finally, the configuration that was evaluated for manual speed control also retained the heave damping augmentation using the chokes. Although this feature is bound to strongly influence the acceptability of flightpath control using the front-side control technique, it was not directly addressed in the work reported here. Instead, an effective value of $Z'_{\alpha}/U_o \doteq -0.8 \text{ sec}^{-1}$ was used so that the investigation could focus on issues associated with modulation of the longitudinal force control. Some background information on the levels of heave damping needed for satisfactory flightpath and flare control is contained in references 5 and 17.

Cockpit Display and Flight Director Configurations

Use was made of a programmable electronic attitude director indicator (EADI) to evaluate the effect of various display and flight director features on the flightpath and speed control tasks. These considerations were thought to be important, particularly for the manual speed control case. In the latter case, the extent to which the pilot was able to employ the same front-side control technique - while maintaining the coordination and alertness necessary to ensure good speed control - might be significantly improved with a flight director that induced a timely and correct response.

The elements of the EADI that were employed are shown in figure 16. These consisted of pitch and roll flight-director bars, a control position director element for the longitudinal force control (nozzle), and a conventional speed-error thermometer-type display.

The pitch flight director used for glidepath control used a control law that assumed a steady-state flightpath-command-to-pitch-attitude gain of 1.0. The law is described in greater detail in the appendix of reference 8, but in summary, its characteristics were:

$$\delta_{PFD} = K_{\gamma}(\gamma_{cmd} - \gamma) - \frac{K_{\theta}s\theta}{s+1} \tag{19}$$

where

$$\left.\begin{aligned} \gamma_{cmd} &= 7.0 - K_{\Delta\gamma}* \text{ (angular MLS beam error)} \\ K_{\gamma} &= 1.0°/\text{deg} \\ K_{\theta} &= 1.0°/\text{deg} \end{aligned}\right\} \tag{20}$$

Strictly speaking, the display gain on flightpath-angle error, K_{γ}, should be modified for along-track winds, since any headwind has the effect of increasing the inertially referenced γ/θ_c response. That is,

$$\frac{\gamma_I}{\theta_c} = \frac{V_A}{V_G}\frac{\gamma}{\theta_c}$$

However, this detail was not implemented for this investigation; as a result, the pitch director bar was somewhat overdriven in moderate headwinds. Nevertheless, the net requirements for corrective adjustments to pitch attitude are reduced in these circumstances and increased in a tailwind.

To maintain nearly stationary control gains during approach, the glidepath control law gain $K_{\Delta\gamma}$ was scheduled with computed slant range to touchdown in the following manner:

$$\left.\begin{array}{ll} R > R_1 & K_{\Delta\gamma} = 3.6 \\ R_1 > R > R_2 & K_{\Delta\gamma} = (3.6)(R/R_1) \\ R_2 > R & K_{\Delta\gamma} = 1.0 \end{array}\right\} \qquad (21)$$

The ranges R_1 and R_2 were chosen as 250 m and 900 m, respectively, corresponding to heights on the nominal -7° glide slope of 110 m (360 ft) and 30.5 m (100 ft). When this pitch flight director control law is combined with equations (8) and (9) representing the pilot's attitude control system and the aircraft with an idealized flightpath-command and speed-hold system, the dynamic characteristics of the controlled element, δ_{PFD}/F_s, which are shown in figure 17, are obtained. These nearly K/s characteristics conform to the well-accepted principles of flight director design, which are described, for example, in reference 18.

In addition to these control laws, a limit of ±4° of flightpath correction on either side of the nominal path was used. This 4° limit constrained control activity to reasonable levels, thus minimizing nozzle saturation. At the same time, it conformed with the glidepath authority requirements suggested in reference 9 for providing satisfactory control in rough air. Pilot comments regarding the suitability of these pitch flight director control laws are included in reference 8 and are discussed subsequently in this report.

The characteristics of the roll flight director used in this investigation for localizer tracking were considered inconsequential to the present objectives. They are reported in reference 8.

The flight director element for the longitudinal force control used the following law, which contained a feed-forward term from pitch attitude in order to induce immediately a compensating input from the longitudinal force control:

$$\delta_{SCD} = \frac{K_D}{0.1s+1}\left[K_u u + (K_\theta \theta - \delta_\nu)\frac{8s}{8s+1}\right] \qquad (22)$$

where K_D, the display gain = 0.3°/deg, K_u = 4.1°/knot, and K_θ = -5°/deg.

The response of the speed-control director element to separate nozzle and pitch control inputs with the glidepath tracking loop open is shown in figure 18 for the 60-knot aircraft data of table 1. The characteristics are nearly those of a constant gain, except for the first-order filtering at 10 rad/sec, used to suppress system noise. Gain-like characteristics, rather than K/s, were found during the research of reference 8 to be more suitable for the propulsion system control, apparently because of manipulator characteristics and the multiaxis nature of the control task. This interpretation assumes the pilot has linear proportional control over the nozzle feedback term δ_v, an assumption most valid for configuration C_{31} which used the aircraft system nozzle levers. When the electric power lever was employed for proportional nozzle control (configurations C_{21}, C_{22}, C_{23}) the pilot had to contend with a 20°/sec rate limit in the electric nozzle servo motor, so that the controlled element dynamics resembled a constant gain only at low input frequencies. When using the nozzle 20°/sec rate switch (configurations C_{41} and C_{43}), the linear representation referred to above is not valid.

The speed-error thermometer scale shown in figure 16 was calibrated at 5 knots per division on either side of center. Like the automatic speed-hold loop, speed-error thermometer was driven by the complementary-filtered combination of airspeed and inertial velocity shown in figure 11, hence reducing its activity in turbulence. Although the pitch, roll, and speed-control director elements could be deleted from the display during any evaluation run (by making an appropriate entry to the avionics system computer), the speed-error thermometer scale was used for all evaluations, as a means of portraying raw speed information in analog form.

TEST ENVIRONMENT AND EVALUATION TASK

The control and display systems just described were evaluated for their effectiveness during straight-in microwave landing system (MLS) approaches in the AWRA in simulated instrument conditions. Pilots who had significant experience in powered-lift aircraft performed the evaluations. Three pilots (A, B, C) who had participated in the research reported in references 6, 7, and 8 performed most of the evaluations; other pilots who provided evaluations are grouped together and designated as pilot D. The specific combinations of control and display configurations tested are shown in table 3, which also specifies the number of evaluation runs made by each pilot. A questionnaire, completed by the pilots after each flight, was the source of the pilot comments discussed in a subsequent section. Four of the questionnaires covering selected configurations are contained in the appendix.

The configurations that involved the use of the path-tracking pitch and roll flight-directors were flown under simulated instrument conditions to a decision height of 30.5 m (100 ft); the configurations employing only raw localizer and glide-slope information presented on the horizontal situation indicator (HSI), shown in figure 10, were terminated at 61 m (200 ft). As discussed subsequently, the evaluation included the flare and landing tasks whenever it was practical to do so, but these considerations are not discussed in depth.

A nominal inertial glidepath angle of -7° was used, and approach airspeeds in the range of 65-70 knots were flown depending on weight. Several evaluation flights were conducted in conditions of light tailwinds, for which the nominal inertial approach angle was adjusted to -6° in order to maintain about the same aerodynamic operating point. A landing flap configuration of 65° and a mean body angle of attack of approximately 6° true (set by an appropriate choice of trim throttle position) resulted in a nominal pitch attitude during approach of about -1°. Some evaluations were carried out in moderate winds (15-25 knots), and in these circumstances, higher approach airspeeds located slightly on the front side of the drag curve were used.

FLIGHT-TEST RESULTS AND DISCUSSION

The results of this investigation are presented in the form of approach time histories, cumulative histograms of pertinent control and performance parameters, and pilot comments and ratings. Each control and display configuration is discussed separately. Representative pilot questionnaires, which were used to enforce a more consistent consideration of the relevant factors, are included for some configurations. Considerations associated with flare and landing, and the use of the integrated electric power lever are discussed following consideration of glidepath and speed-control factors during approach.

The histograms, or probability density functions, that are provided, are intended to simply represent the amplitude distribution characteristics of the data rather than imply statistical significance. The time histories demonstrate the frequency and phase aspects of the multiaxis control task, and the pilot comments and ratings reflect a broad range of practical considerations in the use of this method of glidepath control for powered-lift aircraft. The range of pilot ratings assigned to the configurations to be discussed in this section are summarized in table 3.

Automatic Speed-Control Configurations

As shown in table 3, most evaluation runs were made with configuration C_{11}, primarily because it was used as the baseline configuration at the start of each flight to which the other less sophisticated configurations were to be compared. The data and comments presented here are similar to those contained in reference 8, where essentially the same configuration was also evaluated, but in the context of a curved decelerating approach task having a final straight segment.

A typical time history of the glidepath tracking task in configuration C_{11} is shown in figure 19. This task involves primarily a single control, pitch attitude, since the throttle was essentially fixed during the approach. Occasional adjustments of the throttle may be required to adjust the nominal angle of attack needed, for example, as a result of changes in windspeed during approach. If these considerations are not addressed, the nominal nozzle angle about which control is effected can be biased adversely, resulting in control saturation. (Reference 8 discusses these considerations in greater detail and includes a method for dealing with the situation.) In addition, it is probably desirable to command appropriate throttle changes with a flight director in the event that saturation occurs in the longitudinal force control. As discussed briefly in an earlier section, the throttle could also be incorporated in the automatic system to improve the gain of the flightpath-command system to pitch-attitude inputs. These considerations were not addressed in this investigation, in which the pilot instead adjusted the throttle manually as necessary in order to maintain reasonable approach trim conditions.

The time history shown in figure 19 was obtained during an approach in light turbulence, reflecting what was considered by the pilot to be a fairly low level of control activity. The pitch control inputs at A, B, and C in figure 19 were intentional pilot abuses made to evaluate the stability of the pitch flight director, which had been recently modified to incorporate the control law described earlier. No overshoot or oscillatory characteristics are evident, and indeed the pilot considered the director satisfactory from this point of view, as well as for the precision of control that it provided.

The amplitude distribution of various measures of control input, aircraft response, and system performance in the altitude bands (above ground) between 210 m and 110 m (689 and 360 ft) and 110 m and 30 m (360 and 100 ft) are shown for seven other runs in this control/display configuration in figure 20. Although the data base is not sufficient for statistical significance, these amplitude distributions provide an indication of probable performance under conditions represented by the tests and the amount of control power consumed in achieving this performance. For this and other configurations in which the pitch flight director was used to assist in glidepath control, the control laws over the latter interval are stationary, as described previously. (All other situations involve altitude-sensitive gains, so that the data should be considered as applying to relatively short quasi-stationary segments.)

The units used to indicate the dispersions in flight-director tracking are ones that are meaningful to the pilot. The displacement of the pitch director bar from the aircraft symbol reference point is directly measureable in units of director bar widths, and the deflection of the speed-control director bar from the aircraft symbol (used in the manual modes described later), can be readily scaled against the background pitch attitude ladder (see fig. 16).

It was an objective of the research in reference 8 to evaluate some of the essential considerations in employing the front-side control technique, using an automatic speed-control system for glidepath control in powered-lift STOL aircraft. These considerations, particularly in relation to the alternative backside control technique, are discussed in detail in reference 8, as well as in reference 7, and are reviewed only briefly here. Quoting from reference 8:

> It was generally felt that this control mode yielded a less crisp response for the small precise glidepath corrections which were often desired, at least for the amount and rate of pitch-control input used. All pilots indicated their greater restraint in using aggressive pitch control inputs to accomplish the glidepath control corrections that might, under some circumstances, be commanded by the flight director. In this regard, the physically different nature of throttle and pitch-control inputs should be kept in mind. In the latter case, the glidepath response is achieved through exercising the pitch dynamics, a mechanism of which the pilots (and passengers) are strongly aware through visual and motion cues. In the former case, however, the pilot is able to achieve the desired glidepath change through mechanisms from which he is usually much more detached: throttle position changes, engine dynamics, and aerodynamic circulation effects. In consequence, the pilot is inclined to make throttle-control inputs that are more aggressive and steplike than is the case for pitch. Of course, the pitch dynamics do not permit step inputs in any event, hence contributing to the pilot's notion of apparently slower response in comparison to his relatively unconstrained throttle inputs. Even with the augmentation of heave response to pitch that was incorporated, all pilots felt that pitch-control activity could have become objectionable in more demanding flight conditions, such as moderate or severe turbulence. . . . The pilots generally reported that the glidepath tracking performance that was achieved met their objectives.

In connection with the flight director control laws described earlier, it was noted that "these control laws show good potential for minimizing the pitch-control activity, as measured by pitch rate, that has been identified in the main body of this report (i.e., ref. 8) and elsewhere as being a possibly limiting factor in the use of this glidepath control technique by powered-lift STOL aircraft."

Nevertheless, the pilots did complain about the occasional requirement for moderate to large pitch excursions to correct glidepath errors, with the result that the pilot rating for this configuration ranged between 2½ and 3½ in the light turbulence conditions that were encountered during these tests. (Pilot ratings are based on the scale shown in fig. 21, the use of which is described in detail in ref. 19.)

Reference 7 provides an indication of the improvement that can be achieved by incorporating throttle in the flightpath-command, speed-hold system. As described earlier, this results in increased gain of the flightpath-response to pitch-attitude inputs, and was found in reference 7 to be very effective in improving glidepath response and reducing pitch activity, albeit at the expense of greater system compplexity. For a flightpath gain

$$\left.\frac{\Delta\gamma}{\Delta\theta_c}\right|_{ss} \doteq 1.2$$

and a similar pitch flight director, pilot ratings ranging between 1½ and 2½ were obtained in the same aircraft in similar test conditions.

Returning to the discussion of this flight investigation, the configuration C_{13} employing the automatic speed-control system without flight director, using instead raw localizer and glidepath data presented conventionally on the HSI, received only a few evaluations. Control and performance data did not differ appreciably from the flight director case, although the pilot workload associated with achieving the similar performance levels was higher, primarily because of the increased requirement for instrument scan. Pilot ratings for this configuration were in the range 3-4; thus they are consistent with results reported in reference 7 for another flightpath-command speed-hold system of similar steady-state gain, which was also flown using raw data. Typical pilot questionnaire forms pertaining to these two configurations are contained in the appendix.

Manual Speed Control Configurations

It was the major objective of this investigation to evaluate the capability of the pilot to maintain the same front-side control technique following a failure of the automatic speed-hold system, and to determine the cockpit display configurations that may be required to ensure safe operation. The research of references 7 and 8 and the baseline evaluations of the flightpath-command system with the automatic speed-hold feature just described, provided the experience with the normal system to which the degraded modes were compared. As will be described in this section, it was found that Level II handling qualities[1] could be obtained in the conditions tested by using the speed-control director display. The display provided a prominent and rationally computed command for manually maintaining speed, hence minimizing the possibility of flightpath instability. A secondary area of interest in this investigation was the evaluation of several alternative cockpit controller mechanizations for providing the pilot with control over the two orthogonally oriented propulsion system forces.

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[1]Level II handling qualities, those "adequate to accomplish the mission Flight Phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists," are normally associated with pilot ratings between 3.5 and 6.5 and relate to systems having failure rates of less than 1 per 100 flights; see reference 20.

This section considers the primary controller configuration, identified in table 2, in conjunction with the various display alternatives. A time history is shown in figure 22 for an approach in this primary configuration which used the electric power lever to provide proportional control over the position of the longitudinal force modulating device (the nozzles). For this configuration (C_{21}), the flight director was used to provide pitch and roll steering for path control, and the nozzle director provided commands for speed control. Although the performance is comparable to the automatic case, the increased control activity is reflected in the power lever activity as well as in the apparently increased pitch activity. In addition, there is a single adjustment in the trim throttle setting, at about 250 m (800 ft) agl, deemed necessary by the pilot to reduce the nominal approach angle of attack. This was accomplished with the beep trim switch on the electric power lever shown in figure 15.

Histogram data are shown in figure 23 for seven runs in this configuration, all in conditions of light turbulence.

This configuration (C_{21}) was designed to provide the greatest assistance to the pilot for manual speed control by employing a proportional longitudinal force control in conjunction with a controller director. However, the pilots had some difficulty coordinating the use of nozzle and pitch controls. In some cases, oscillatory tendencies were excited in the speed-control director loop which occasionally coupled into the pitch loop. This problem probably reflects the fact that the director is not wholly effective for inducing the closely coordinated nozzle inputs that are required whenever pitch is adjusted. The pilot seems to require that his own internal gearing be developed (as is done with practice) in order to precondition his response to the nozzle director element. Most pilots considered it unreasonable to expect this internal coordination to be developed quickly following a failure of the normal automatic system, with the result that there is increased importance attached to a well-designed and appropriately displayed speed-control director. The occasional difficulty in the control of this director element is also perhaps a result of the direct crossfeed term from pitch (eq. (22)), which sometimes could cause some confusing behavior of the nozzle director bar if this effect was not well understood by the pilot.

In addition to these director-related factors, all pilots considered that the 20°/sec rate limit that prevailed between the electric power lever and the aircraft nozzles (a limitation of the electric servo commanded by the power lever position) could be largely responsible for the sometimes oscillatory behavior of the speed-control director bar. The control position feedback to the director used nozzle position rather than the power lever position. In addition, a hysteresis band approximately 8° in width which existed in the aircraft's nozzle drive mechanism provided another possibly significant nonlinearity.

To complete this discussion on the effect of the director, the presence of the pitch director bar was compelling enough to ensure that the pilot continued to employ pitch attitude to track the glidepath. Consequently, the additional tasks imposed on the pilot in this configuration involved scanning and nulling the speed-control director bar using appropriate displacements of the electric power lever. Some complaints were noted concerning the noticeably higher workload involved in closing the pitch and nozzle loops at similar frequencies. This is reflected in the pilot ratings for this configuration, which ranged between 3½ and 4½. A pilot questionnaire for configuration C_{21} that relates to the time history of figure 22 is contained in the appendix.

When the pitch and roll flight directors were removed (configuration C_{22}), it is significant to note that the programmed relationship of the nozzle director to speed control appeared to be sufficient to allow the pilot to continue to use pitch for glidepath control without confusion. Although in these circumstances it was an instrument approach task using raw data that was being considered, the same confidence in being able to maintain the same front-side control technique during a visual approach might also follow, particularly if the speed-control director were prominently displayed, such as on a head-up display. Some visual approaches in this configuration were indeed flown with great success and low workload. However, tight precision constraints were not placed on making the landing zone so that maneuvering and precision demands were not high.[2]

A typical time history of an approach in configuration C_{22} is shown in figure 24, and the corresponding histogram data for six approaches is presented in figure 25. The time history indicates fairly low-gain control of glide slope, and less precise performance.

The typical complaints about this configuration had to do with the requirement to manage two raw data loops for localizer and glide slope and at the same time closing a fairly high-frequency loop on the nozzle director. Although the task is similar to a conventional instrument landing system (ILS) approach task, the more stringent control and display monitoring requirements imposed by the speed-control task when operating on the backside of the drag curve impose a significant additional workload that is reflected in pilot ratings for this configuration that are in the range 4½ to 5.

A further degradation was made to this configuration by removing the speed-control director (configuration C_{23}). The speed-error thermometer scale was retained, because it was considered unrealistic not to have some form of analog speed scale to effectively portray at least raw deviations from a reference. A time history for an approach in this configuration is shown in figure 26. The performance achieved in all axes is quite good, and the control activities are quite reasonable. However, the high workload associated with managing three active raw data control loops is reflected in the pilot comments contained in the corresponding questionnaire (see the appendix), and the associated pilot rating of 6. The immediately previous approach of a series flown by this pilot is shown in figure 27, where the discontinuous attention given to controlling the various axes is evident. To compound matters, there was also a requirement during this approach to make a single adjustment of the throttle to reduce the nominal angle of attack. In referring to these difficulties, another pilot commented that the "scan pattern was frequently full of surprises." No histograms are included for this configuration because of these sometimes large excursions.

It was universally felt that this configuration did not provide an adequate level of assurance that satisfactory speed control could be effected while performing

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[2]It should be emphasized that the investigations of flightpath control using nozzle modulation (throttle essentially fixed) which have been previously reported all pertain to the instrument approach task. Yet there is considerable experience with this aircraft that indicates that visual approaches, at least to relatively unconfined landing areas, can be carried out satisfactorily (PR $<$ 3), even in quite severe turbulence, using nozzle modulation. However, the technique still involves changing from nozzle to throttle levers just before flare entry (typically), in anticipation of the necessary throttle reduction after landing, as well as the possible need for more responsive control over gust or shear disturbances close to the ground.

the precision approach task; or conversely, it was felt that the approach task precision would suffer unacceptably if good speed control were to be maintained. These concerns would presumably intensify in more adverse flight conditions, such as turbulence or shears. As a result, it is concluded that the pilot could not be expected to perform the raw data instrument approach task following a failure of the automatic speed control using the same front-side control technique unless a prominently displayed speed-control director was provided. (The alternative possibility of providing just a pitch-roll flight director was not evaluated but might be expected to improve the situation.)

There was no report of confusion over technique in this wholly unassisted configuration. However, it is probable that the emphasis of this flight investigation on the failure modes, which were typically evaluated somewhat systematically in a routine of increasing degradation, did not present the pilots with a realistic requirement to suddenly encounter the need to use an unanticipated change in piloting technique. Also affecting the pilot's ability to quickly adapt to the failure technique is the design of the cockpit control used for speed management, as discussed next.

Configurations Employing Alternative Cockpit Controller Mechanizations

Two alternative mechanizations for providing the pilot with control of the longitudinal propulsive forces were evaluated. In the first instance, denoted configuration C_{31} in table 2, the nozzle control levers located on the overhead control panel were used. This allowed direct control of the nozzles (at rates up to 100°/sec, the capability of the aircraft system pneumatic servo motor), without suffering the nonlinear bandwidth-limiting effects of the parallel electric servo, which characterized the electric power lever implementation. This mechanization also retained the interconnect feature, using the chokes to minimize any lift-loss effects when retracting nozzles, and also provided the augmented heave damping.

Configuration C_{31} was evaluated in conjunction with the speed-control and pitch-roll flight directors, and is comparable to configuration C_{21}, which used the rate-limited electric power lever. As seen in the time history shown in figure 28, nozzle-angle corrections are step-like, effected with very stable behavior of the speed-control director element (e.g., at point A). This reflects the gain-like characteristics of the displayed element. It is a good manifestation of the facility of

[3]There was concern that the technique used after failure of the automatic speed-hold system might have been confused in one of two possible ways. On the one hand was the possibility that the nozzle might have been considered the glidepath controller and pitch the speed controller. This philosophy was adopted in the early days of operating this aircraft and stemmed from considering mainly the trim effects of controls as portrayed in figure 6, also reflecting the backside or near-backside operating procedure for swept-wing jet aircraft on approach. Indeed, this technique may be satisfactory for the lower frequency visual approach task, which was the context in which this philosophy had evolved. In the present study, however, active modulation of pitch directly for glidepath control was promoted as being needed to achieve satisfactory short-term heave response made necessary by the instrument approach task. Alternatively, the pilot might be inclined to revert to the use of throttle for glidepath control, not of itself an unsatisfactory alternative, provided other factors (such as his training, his adaptability, and the availability of control devices and control power) allow it.

this design approach in allowing the pilot to take advantage of controls that can be rapidly positioned and then temporarily ignored while other control loops are serviced. For the approach shown, which was conducted in light turbulence but with 15-20-knot headwinds (hence the more positive trim pitch attitude and lesser mean nozzle angle), the pilot rating was 3½. One disadvantage of this control mechanization is the requirement to change back and forth between the throttle and the nozzle levers for any power changes that might be necssary, such as is indicated at B in the figure.

This configuration did not receive universally good ratings. The pilot (B) who had experienced an oscillatory tendency with the pitch director in the comparable configuration C_{21} encountered similar though reduced tendencies here, and assigned the same rating of 4½. Pilot A, who evaluated this configuration in moderate low-frequency turbulence, rated it at 5½, citing continued difficulty in coordinating nozzle with pitch, although he reported that the directors were easy enough to follow. He suggested removing the direct crossfeed term from pitch-attitude changes to the speed-control director so that its behavior would be more obvious to the pilot, reflecting speed errors as they developed rather than anticipating them as was implemented. Although adequate training might be the usual solution to this type of difficulty, the objective of this investigation to provide adequate levels of performance with acceptable workload following a failure of the normal system imposes more severe requirements for a system to which the pilot can easily adapt.

Amplitude distribution histograms for five approaches with this configuration are presented in figure 29.

The other mechanization for nozzle control used the nozzle rate switch on the electric power lever (see fig. 15 and table 2). In this implementation, the proportional function of the lever was connected to the throttles, hence providing what is perhaps the most practical design alternative for integrating the two propulsion system controls into a single controller. In evaluating this configuration C_{41} it was assumed that the failure of the automatic speed-hold system was such that manual control of the longitudinal force device in this manner could still be effected.

A time history of an approach by pilot B in configuration C_{41} employing the nozzle rate control in conjunction with the speed-control and pitch-roll flight directors is shown in figure 30. The moderate headwinds during this approach again account for the more positive nominal pitch attitude and lesser mean nozzle angle. As indicated in the corresponding questionnaire (see appendix) and as is strongly evident in the figure, high-frequency oscillatory characteristics are evident in pitch, and a much lower frequency oscillation is apparent and was reported in the speed-control loop. As can be seen from the character of the pitch attitude time history, the speed-loop oscillation understandably couples into the glidepath tracking loop. The severity of these problems is likely influenced by the moderate turbulence level that was reported; it is reflected in the pilot rating of 5½.

The increased attention that must be devoted to the speed-control loop is reflected in the increased number of control inputs seen in figure 30. For the interval shown, the nozzle rate switch was activated about 25% of the time. Together with the continuous column and wheel activity involved in tracking the pitch and roll directors, this characterizes an unusually high level of control activity. Contributing to the problems in the speed-control loop was a hysteresis of about 8° in the aircraft nozzle positioning system. It is speculated that unusually high pilot gain contributed to the intensity of the high-frequency pitch oscillation that was experienced. It is noteworthy that other pilots did not excite this problem. To assist in alleviating the nozzle control problem, a higher gain on the nozzle rate switch was suggested; however, the maximum available rate of 20°/sec was implemented for this investigation. It is quite possible that a higher rate and elimination of the hysteresis problem could result in significantly more acceptable control than was attainable in these tests.

It is considered that the major source of difficulty with this configuration is related to the nonlinear fixed-rate characteristics of the controller, characteristics which appear very unsuited to the high-frequency nature of the control task. On the other hand, this method of control seemed to be much more acceptable whenever task constraints were reduced during several undocumented visual approaches.

Despite its utility in prominently displaying existing speed errors or speed errors likely to develop, it was speculated that the speed-control director alone, in the absence of pitch-roll directors, could actually detract from overall task performance if used for a raw data instrument approach. This was partly a result of its nonlinear integral characteristics; these characteristics demanded excessive attention to null this display element when in fact a wider instrument scan was necessary. Although configuration C_{42} was not evaluated to assess the validity of this speculation, several evaluations were made without the presentation of any director information. This latter configuration C_{43} might be considered the most degraded, although the possibility just promoted that C_{42} (if the director element is used) might be more difficult, should be kept in mind.

A time history for configuration C_{43} is presented in figure 31. It reflects the same problems of tracking with raw data the three active loops of glidepath, localizer, and speed which were evident for configuration C_{23}. In this situation, the speed loop requires even more attention because of the nature of the nozzle controller; consequently the pilot ratings were in the 6 to 7 range, reflecting what are apparently unacceptable Level II handling qualities in realistic operational flight conditions. No amplitude distribution histograms are furnished for these nozzle-rate configurations because of the relatively few evaluations that were conducted.

Flare and Landing Considerations

Pilot technique and associated performance during landing are concerns in the use of flightpath command speed-hold systems for STOL aircraft. Some of the constraints peculiar to STOL operations are the requirements for large reductions in flightpath angle after clearing possible approach-end obstacles, precision touchdowns, and minimum rollout distances. Although the nominal landing technique would typically involve some speed bleed-off during flare, which would reduce the runway deceleration requirements after touchdown, the automatic speed-hold system would require additional intelligence to rationally effect this. On the other hand, it might be that reduced approach airspeeds could be allowed, using an automatic speed-hold system, since it might be possible to maintain safety margins more reliably. At the same time, the artificially improved heave damping operating in conjunction with what is effectively increasing longitudinal thrust as the aircraft is rotated, may provide unnecessary flare capability, requiring considerable pilot skill to prevent overflaring to ensure repeatably precise touchdowns. Some of these considerations for the automatic speed-hold cases are discussed in considerable detail, with supporting data in references 7 and 8.

A somewhat different set of considerations is involved for the situation in which an approach has been carried out using the front-side control technique but with speed-control accomplished manually. Although there may generally be available adequate flarability through pitch rotation alone (if close enough to the nominal speed and angle of attack), the pilot seems to want to have direct control of the throttles in order to augment or reduce this heave response to pitch, should conditions, such as turbulence or shear, suddenly warrant. In addition, there is the usual requirement to immediately reduce power after landing. When two separate proportional controls are used for management of the orthogonal propulsion system forces (configuration C_{31}), the pilot will typically need to change controllers sometime before flare. Moreover, those configurations in which the throttle control was integrated into the electric power lever control as a beep trim switch, do not appear satisfactory for the high-frequency precision throttle control requirements of the landing task. In addition, the controller configuration in which the apparently necessary proportional throttle control was integrated with the nozzle-rate switch on the electric power lever appears to be an unacceptable solution because of the nozzle control difficulties described earlier.[4]

In addition to these considerations, there is the requirement to set and leave the longitudinal force control at some particular position appropriate to the aircraft's state when flare is entered. This in itself can have the beneficial effect of allowing a more typical speed reduction through flare, provided deviations from the nominal flight conditions are small and atmospheric disturbances are not excessive. A further concern occasionally raised by the pilots was about the lack of familiarity with throttle effectiveness resulting from not having used the throttle for precision control during the approach. In some instances, the pilot would make a number of small rapid throttle inputs just before flare to provide the desired familiarity should its use be necessary. In most instances, the flare technique consisted of rotating the aircraft to arrest sink rate and immediately retarding the throttle touchdown, as examplified in figure 31.

Although landing precision was not measured in this investigation, no particular problems in addition to the considerations just mentioned arose during these evaluations. Taking into account the emphasis of this investigation on Level II handling qualities, the major requirement identified as a result of the flare and landing task was for a proportional throttle control allowing rapid and precise modulation of the normally oriented propulsion system forces.

CONCLUSIONS

This flight investigation examined the feasibility of using the front-side control technique during piloted approaches in a powered-lift aircraft operating on or near the backside of the drag curve. The availability of substantial longitudinal propulsive thrust, which could be modulated without significantly affecting the level of powered-lift, was used to provide speed control while tracking the glidepath with pitch attitude. The use of an automatic speed-hold system, found during previous research and again in this work to be an acceptable means of providing satisfactory flying qualities during simulated instrument conditions, was reviewed and some of its advantages and disadvantages discussed. Although a range of characteristic parameters has not been thoroughly investigated, it would appear from available data that minimum values of $|\Delta\gamma/\Delta\theta| \doteq 0.9$ and $Z'_\alpha/U_o \doteq -0.5$/sec are required for satisfactory flying qualities when a flightpath-command and automatic speed-hold system is used for glidepath tracking. The desirability of a system providing $|\Delta\gamma/\Delta\theta|_{ss} > 1.0$ by incorporating the powered-lift (throttle) control in the automatic system was

[4]During these investigations, landings typically were not made using the electrically servoed throttle because of bandwidth limitations and hysteresis problems.

demonstrated in reference 7 where a value $|\Delta\gamma/\Delta\theta|_{ss} \doteq 1.2$ received excellent pilot ratings. This improvement is recommended in principle here, although this would raise a new set of system complexity, realiability, and failure issues that were not addressed in this investigation.

An automatic speed-hold system described as $|\Delta\gamma/\Delta\theta|_{ss} \doteq 1.0$, $Z'_\alpha/U_o \doteq 0.8$ sec was then used as the basis for comparison when evaluating various manual speed-control configurations. These involved the pilot modulating the longitudinal thrust device himself, as could be required following a failure of the automatic system. Both proportional and rate control of the longitudinal force device were evaluated in conjunction with the use of pitch and roll flight directors for flightpath control, and a longitudinal force control director for speed control. It was determined that a prominently displayed speed-control director, in conjunction with a proportional longitudinal force controller, was required to provide acceptable flying qualities for the precision MLS approach task (with or without a pitch-roll director for flightpath control), in the context of military Level II criteria.

Although the degree of backsidedness encountered in this investigation was not severe (ranging between 0.2° to -0.05°/knot), and of itself posed no significant problem for the pilot, it would be expected that operating points located more on the backside could be troublesome. Other flight test data reported in references 6 and 13, for which a range of backside operating points was considered, indicated an onset of difficulties related to this factor for $d\gamma/dV > 0.3°/\text{knot}$. However, the referenced investigations involved use of the backside control technique, so that a more critical set of considerations may be involved in the present context. That is, without automatic longitudinal thrust control, use of pitch attitude for glidepath control is more directly destabilizing than the secondary effects typically encountered during use of the backside control technique. Further investigation of the importance of this parameter for the front-side control technique seems warranted.

It should be emphasized that the acceptability of the systems and control techniques investigated here may be altered significantly under different operating conditions. In one respect, the proportional controller configurations evaluated here appear to be quite satisfactory during relatively unconfined visual approaches, although some type of prominently presented speed-control director or speed-error display is considered necessary. In another respect, the effect of an engine failure may require special design features for both the failed and the unfailed speed-control system. These are areas requiring investigation.

It was determined during these tests that the most important consideration in the manual control technique evaluated was the nature of the pilot's propulsion system controller. To exploit for manual control the considerable flexibility of two separate and nearly uncoupled propulsion system controls seems to require an appropriate single control handle incorporating proportional control over each device in a clear and unconfusing manner. Other features, such as an adjustable detent to identify a trim position, may also be desirable. There is a need for newly engineered pilot controls for powered-lift aircraft to investigate these and other concepts.

A number of programs have been conducted with this aircraft over recent years in which pilots having a variety of flight experience have been involved. It has become apparent from a pilot point of view, that there may indeed be certain advantages in equipping the aircraft with the capability to be flown using a technique that is consistent throughout the entire flight envelope. Particularly for pilots having a background in conventional aircraft, the use of the front-side control technique for powered-lift aircraft appears appropriate, provided the necessary supporting systems such as those discussed in this report are incorporated. Admittedly, significantly greater sophistication is necessary to provide continuity throughout the entire flight envelope, especially during the transition between CTOL and STOL flight regimes. Nevertheless, the systems evaluated in this investigation have provided additional data on the characteristics required and on the consequences of system failure, in endeavoring to provide this front-side control capability.

APPENDIX

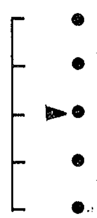
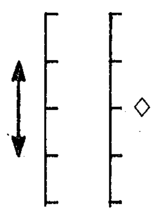
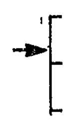
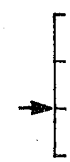
SELECTED PILOT QUESTIONNAIRES

FRONT-SIDE CONTROL QUESTIONNAIRE

Pilot A Flight No. 664 Configuration C_{21}

Number of approaches 2 Winds and turbulence moderate winds with some cross-wind - light turbulence

1. GLIDEPATH AND SPEED CONTROL

	Indicate mean range of precision achieved	Indicate your own judgment of adequacy of precision, taking into account the atmospheric conditions	Indicate the degree of difficulty encountered in achieving the desired precision
Glidepath control	Did not notice HSI performance FD seemed reasonable  1 dot = 0.86° elevator error	 good fair poor	 none slight moderate great
Speed control	 1 dot = 5-knot speed error	 good fair poor	 none slight moderate great

• Nature of difficulties

Glidepath: None - followed flight director which seemed to give good results.

Speed: Tendency for oscillatory nozzle inputs.

• Most desirable features

Control (including pilot's controller): I like the integrated control over nozzle and thrust in one power lever - can adjust thrust while controlling nozzles. Flight-path seems quite responsive to pitch.

Display: Following the director commands, without working too hard at it, seems to give good results for tracking glidepath, localizer, and speed.

• Most objectionable features

Control: Need to relearn how to coordinate pitch and nozzle. Power (nozzle) lever deflections seem fairly large to maintain speed.

Display: Occasional display clutter and symbology overlay. Difficult to interpret performance on EADI alone without reference to HSI.

• Effect of lateral task on longitudinal factors: Minimal.

• Pilot rating (for conditions flown): 3

• Recommendations for improvement: Increase gain on power (nozzle) lever.

2. FLARE AND LANDING

- Technique employed: Flared with pitch, reduced thrust to accomplish (had transferred to overhead aircraft controls by then).

- Precision obtained (touchdown point, sink rate control): Poor, I think, because I needed more practice to adjust to new improved heave characteristics relative to previous landings.

- Comment on need for special effort to maintain safety margins through flare, and how accomplished:

- Most desirable features: Adequate heave response to pitch.

- Most objectionable features: Having to switch to thrust control (throttles) to accomplish touchdown when I haven't actively used it during approach.

- Pilot rating: 3

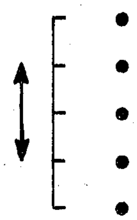
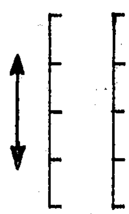
- Recommendations for improvement of flare task: Could do a more gradual flare starting earlier minimizing need to reduce thrust to land.

FRONT-SIDE CONTROL QUESTIONNAIRE

Pilot B Flight No. 687 Configuration C_{23}

Number of approaches 2 Winds and turbulence Strong crosswind from right, light turbulence, some moderate shear suspected.

1. GLIDEPATH AND SPEED CONTROL

	Indicate mean range of precision achieved	Indicate your own judgment of adequacy of precision, taking into account the atmospheric conditions	Indicate the degree of difficulty encountered in achieving the desired precision
Glidepath control	 1 dot = 0.86° elevator error	good fair poor	none slight moderate great
Speed control	 1 dot = 5-knot speed error	good fair poor	none slight moderate great

- Nature of difficulties

Glidepath: The big problem with glidepath, speed, and localizer was the high work-load in closing all loops together.

Speed: There are too many high frequency raw data loops, especially with cross-winds and shears. High potential for not maintaining adequate performance in one or more loop(s) while concentrating on the other(s).

- Most desirable features

Control (including pilot's controller): No problem with electric power lever, including making a small power adjustment with beep trim switch on one approach.

Display: A flight director providing at least speed control direction would help.

- Most objectionable features

Control: The rate limit on the nozzles (they don't move as quickly as I command them to with the power lever) is mildly objectionable.

Display: Too many high frequency raw data loops to close, with their information dispersed over a wide scan area (EADI and HSI).

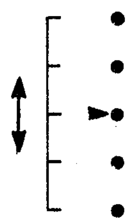
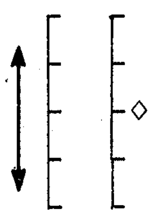
- Effect of lateral task on longitudinal factors: The lateral task had a significant effect with the crosswind present. Also the lateral channel requires equal attention with pitch and nozzle.
- Pilot rating (for conditions flown): 6
- Recommendations for improvement: Need some kind of flight director - speed control and/or pitch-roll control.

FRONT-SIDE CONTROL QUESTIONNAIRE

Pilot B Flight No. 687 Configuration C_{41}

Number of approaches 1 Winds and turbulence Moderate winds, turbulence and crosswind, possibly some moderate shears.

1. GLIDEPATH AND SPEED CONTROL

	Indicate mean range of precision achieved	Indicate your own judgment of adequacy of precision, taking into account the atmospheric conditions	Indicate the degree of difficulty encountered in achieving the desired precision
Glidepath control	 1 dot = 0.86° elevator error	→ good fair poor	none slight → moderate great
Speed control	 1 dot = 5-knot speed error	→ good fair poor	none slight moderate → great

- Nature of difficulties

Glidepath: High-frequency low-amplitude pilot induced oscillation (PIO) in pitch could be felt in heave response but did not disturb glidepath significantly.

Speed: Low-frequency oscillatory characteristics couple into pitch. Excessive attention required to operate nozzle rate switch and watch for speed control director to null itself. Uncertain about actual location of nozzles, e.g., close to saturation?

• Most desirable features

Control (including pilot's controller): The only desirable feature of this control mechanization is that throttle is now consistently available in a proportional sense on the power lever control.

Display: At least the display scan is adequately confined - basically restricted to EADI. Still, each element of symbology needs to be scanned.

• Most objectionable features

Control: Excessive attention required to null speed director - sometimes undershoot it, sometimes overshoot. A higher trim rate might help and with more experience would learn to integrate better, but still must service other loops while rate switch held.

Display: High frequency pitch PIO.

• Effect of lateral task on longitudinal factors: Not significant, roll director bar is easy to scan. Nevertheless, workload about 50% higher than if needing to manage just pitch and nozzle.

• Pilot rating (for conditions flown): 5½

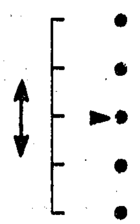
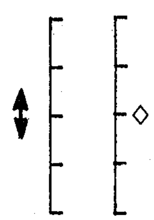
• Recommendations for improvement: Increase gain on nozzle rate command?

FRONT-SIDE CONTROL QUESTIONNAIRE

Pilot C Flight No. 690 Configuration C_{11}, C_{13}

Number of approaches 1 each Winds and turbulence Light, but noticeable turbulence.

1. GLIDEPATH AND SPEED CONTROL

	Indicate mean range of precision achieved	Indicate your own judgment of adequacy of precision, taking into account the atmospheric conditions	Indicate the degree of difficulty encountered in achieving the desired precision
Glidepath control	 1 dot = 0.86° elevator error	→ good fair poor	→ none slight moderate great
Speed control	 1 dot = 5-knot speed error	→ good fair poor	Not applicable → none slight moderate great

• Nature of difficulties

Glidepath: No problems - can concentrate all longitudinal control effort on glidepath knowing speed is looked after.

Speed: None - automatic system gives good performance - occasional threat of saturation, however, which could become a problem in turbulence, shear, or during large corrections.

• Most desirable features

Control (including pilot's controller): Single control requirement - no (or little) requirement to employ throttle. Rate command attitude hold SAS provides good pitch control.

Display: Flight director nicely integrates lateral and vertical path control tasks. Without flight director, scan requirements noticeably higher.

• Most objectionable features

Control: Pitch activity, though not extreme during these atmospheric conditions, is mildly objectionable together with associated changes in cockpit noise level due to nozzle activity.

Display: Occasional clutter due to symbology overlay if using flight director.

• Effect of lateral task on longitudinal factors: No effect when using flight director - without flight director, increased scan requirements can cause temporary inattention to other axis resulting in occasional need for larger corrections.

• Pilot rating (for conditions flown): 3 with Flt. Dir., 3½ without Flt. Dir.

• Recommendations for improvement: Incorporate intelligence into flight director on what to do if the speed control system saturates, i.e., temporarily add or reduce power.

2. FLARE AND LANDING

- Technique employed: Fairly aggressive rotation, dragging off power prior to touchdown to prevent overflaring and avoiding float. Requires some practice.

- Precision obtained (touchdown point, sink rate control): Good repeatable precision after several practice landings - but unfortunately, inconsistent performance on initial landings or if atmospherics are variable.

- Comment on need for special effort to maintain safety margins through flare, and how accomplished: No problems - speed of no concern, flarability of no concern, angle of attack and sink rate control assured since backing up with throttles.

- Most desirable features: Speed hold allows full attention outside cockpit to employ height and sink rate cues for desired precision.

- Most objectional features: Inconsistent landing performance until technique developed or unless in practice.

- Pilot rating: 3½

- Recommendations for improvement of flare task: Somehow incorporate an appropriate speed reduction during rotation - there is excess capability to flare in normal conditions taking into account augmented heave damping and speed hold feature.

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TABLE 1.- SUMMARY OF PRINCIPAL STABILITY DERIVATIVES AND STEADY-STATE RESPONSE CHARACTERISTICS FOR THREE REFERENCE FLIGHT CONDITIONS

Stability derivative	U_o = 60 knots γ_o = -7.5°	U_o = 69 knots γ_o = -7.5°	U_o = 85 knots γ_o = -6.2°
X_u, 1/sec	-0.052	-0.068	-0.073
X_α/U_o, 1/sec	0.15	0.12	0.068
X_{δ_ν}/U_o, 1/sec	-0.0485	-0.035	-0.041
Z_u, 1/sec	-0.29	-0.31	-0.24
Z_α/U_o, 1/sec	-0.52	-0.52	-0.61
Z_{δ_ν}/U_o, 1/sec	0	-0.012[a]	-0.007[a]
W, kN (lb)	178 (40,000)	178 (40,000)	191 (43,000)
Flap angle, deg	65	65	50
δ_{ν_o}, deg	90	70	80
Hot thrust, kN (lb)	28.4 (6,380)	25.1 (5,632)	37.5 (8,424)
θ_o, deg	-4.7	-2.0	-5.4
C_j	0.45	0.32	0.29
$(\Delta\gamma/\Delta\theta)_{ss}$, deg/deg	0.93	0.94	0.96
$(\Delta\delta_\nu/\Delta\theta)_{ss}$, deg/deg	-6.72	-8.0	-5.5
$d\gamma/dV$, deg/knot	0.27	0.15	-0.05

[a]Assumed 0 because of lift compensation with chokes.

TABLE 2.- COMBINATIONS OF MANUAL PROPULSION SYSTEM CONTROLS EVALUATED

	Proportional throttle	Rate throttle
Proportional nozzle	Overhead throttle lever[a] overhead nozzle levers (configuration C_{31})	Electric power lever throttle rate switch (configurations C_{21}, C_{22}, C_{23})
Rate nozzle	Electric power lever nozzle rate switch (configurations C_{41}, C_{43})	Not evaluated

[a]Primary evaluation case.

TABLE 3.- SUMMARY OF FLIGHT EVALUATIONS

	Pitch-roll and speed-control directors				Speed-control director alone				No director bars			
	Configuration	Pilot	Number of evaluation runs	Range of pilot ratings: approach task	Configuration	Pilot	Number of evaluation runs	Range of pilot ratings: approach task	Configuration	Pilot	Number of evaluation runs	Range of pilot ratings: approach task
Automatic speed hold	C_{11}	A B C D	3 4 3 5	2.5 to 3.5					C_{13}	A B C D	1 1 1 2	3 to 4
Proportional nozzle control, using electric power lever	C_{21}	A B C D	3 3 4 2	3.5 to 4.5	C_{22}	A B C D	2 2 3 1	4.5 to 5	C_{23}	A B C D	0 2 2 0	6
Proportional nozzle control, using overhead nozzle levers	C_{31}	A B C D	2 2 1 1	3.5 to 5.5								
Rate control of nozzles, using trim switch on electric power lever	C_{41}	A B C D	0 2 2 1	5.5					C_{43}	A B C D	0 2 1 0	6.0 to 7.0

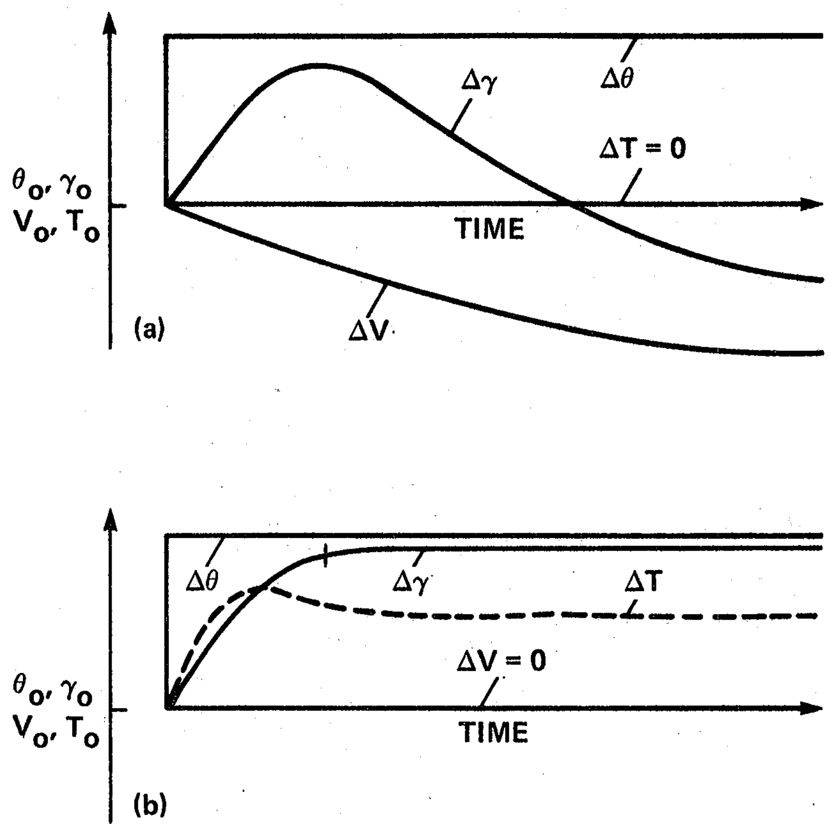


Figure 1.- Flightpath and speed response to a step change in pitch attitude for an operating point on the backside of the drag curve.

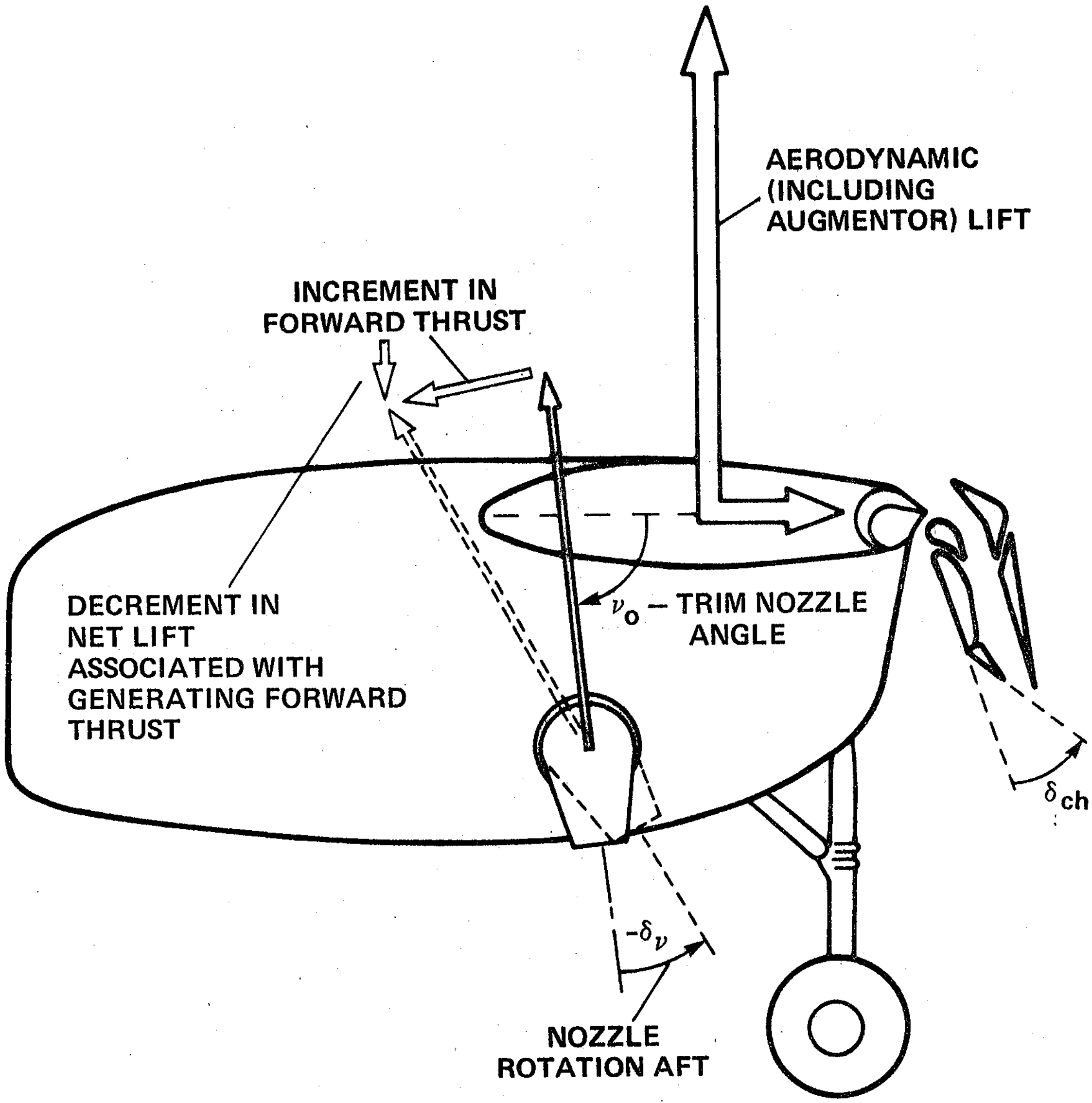


Figure 2.- Coupling of longitudinal thrust modulation with lift.

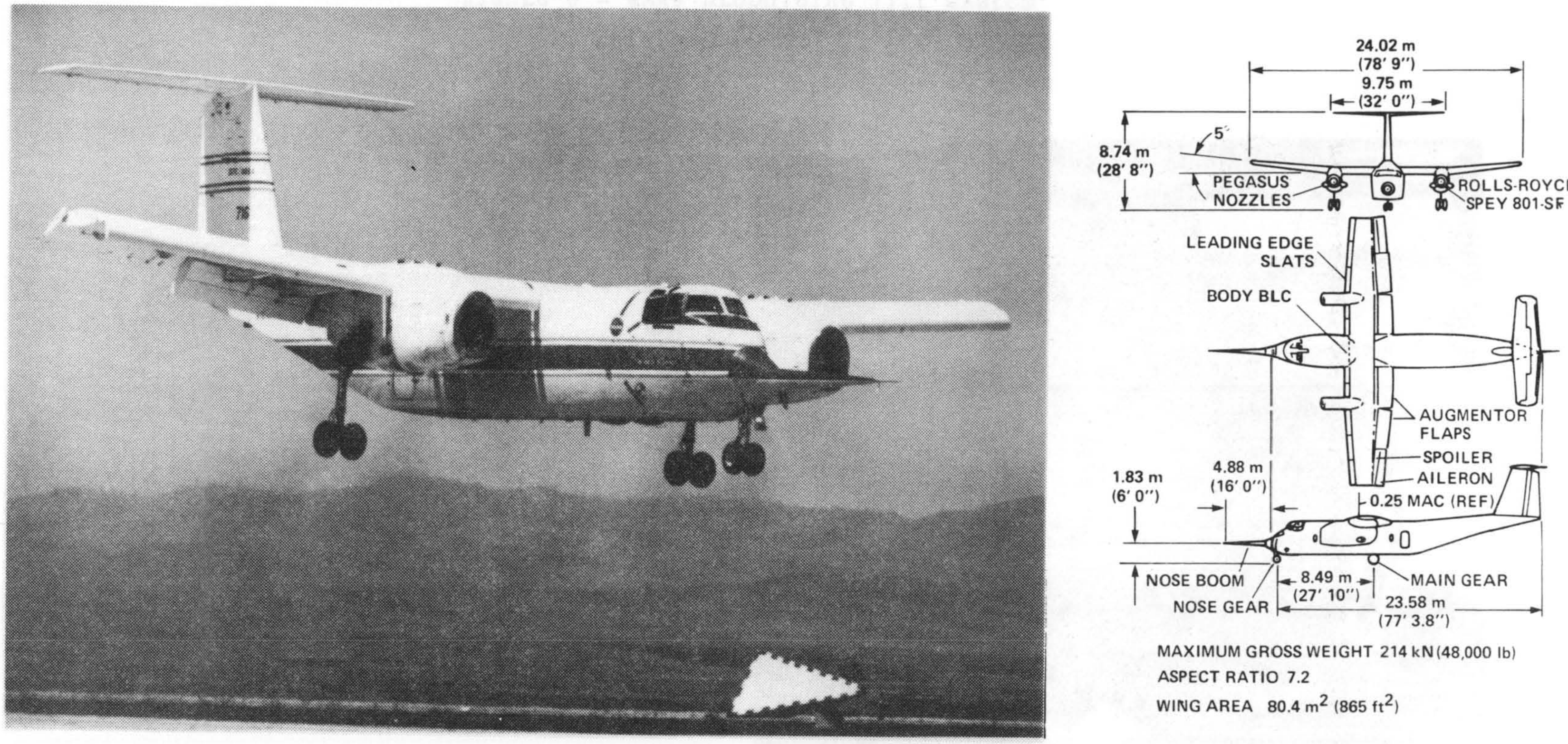


Figure 3.- Augmentor Wing Research Aircraft.

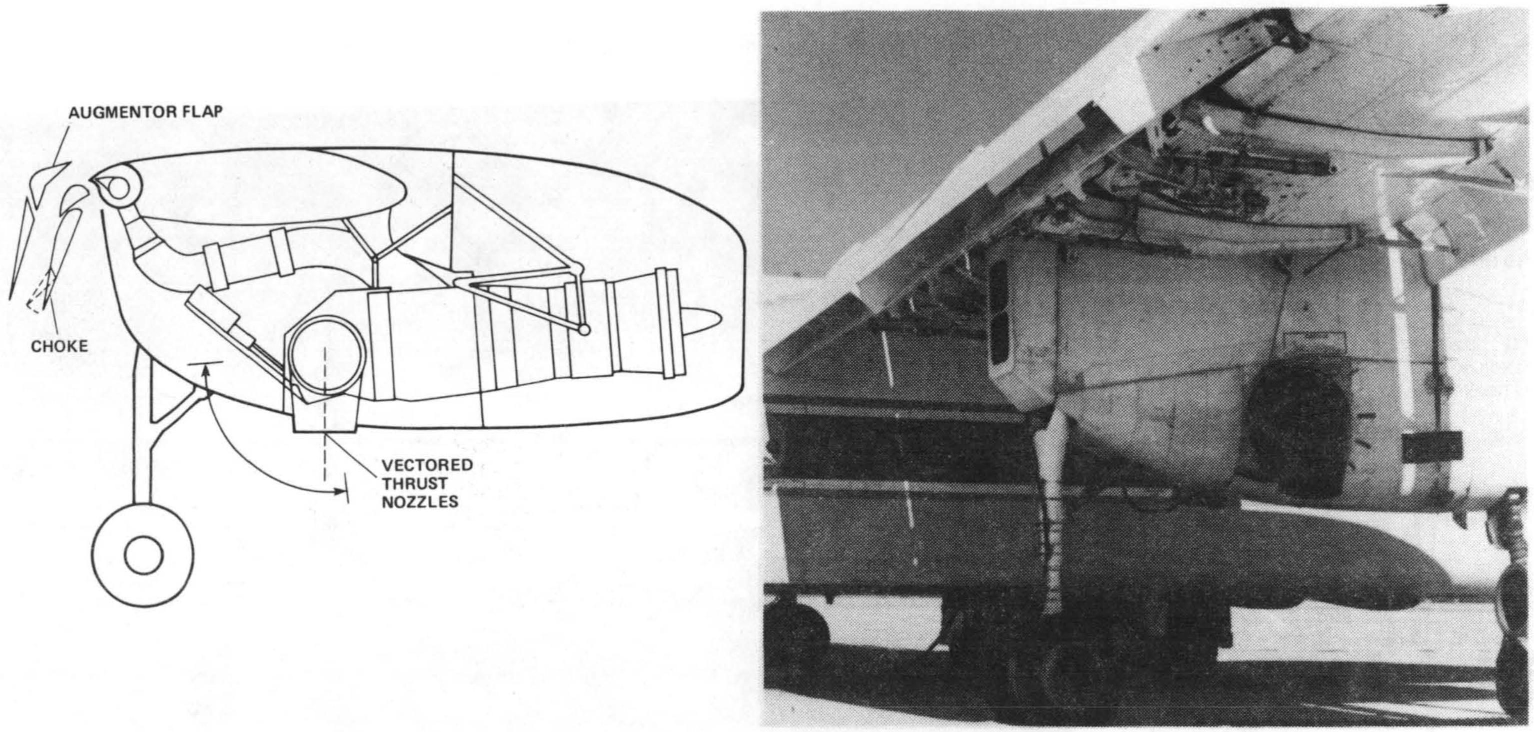


Figure 4.- AWRA propulsive lift system.

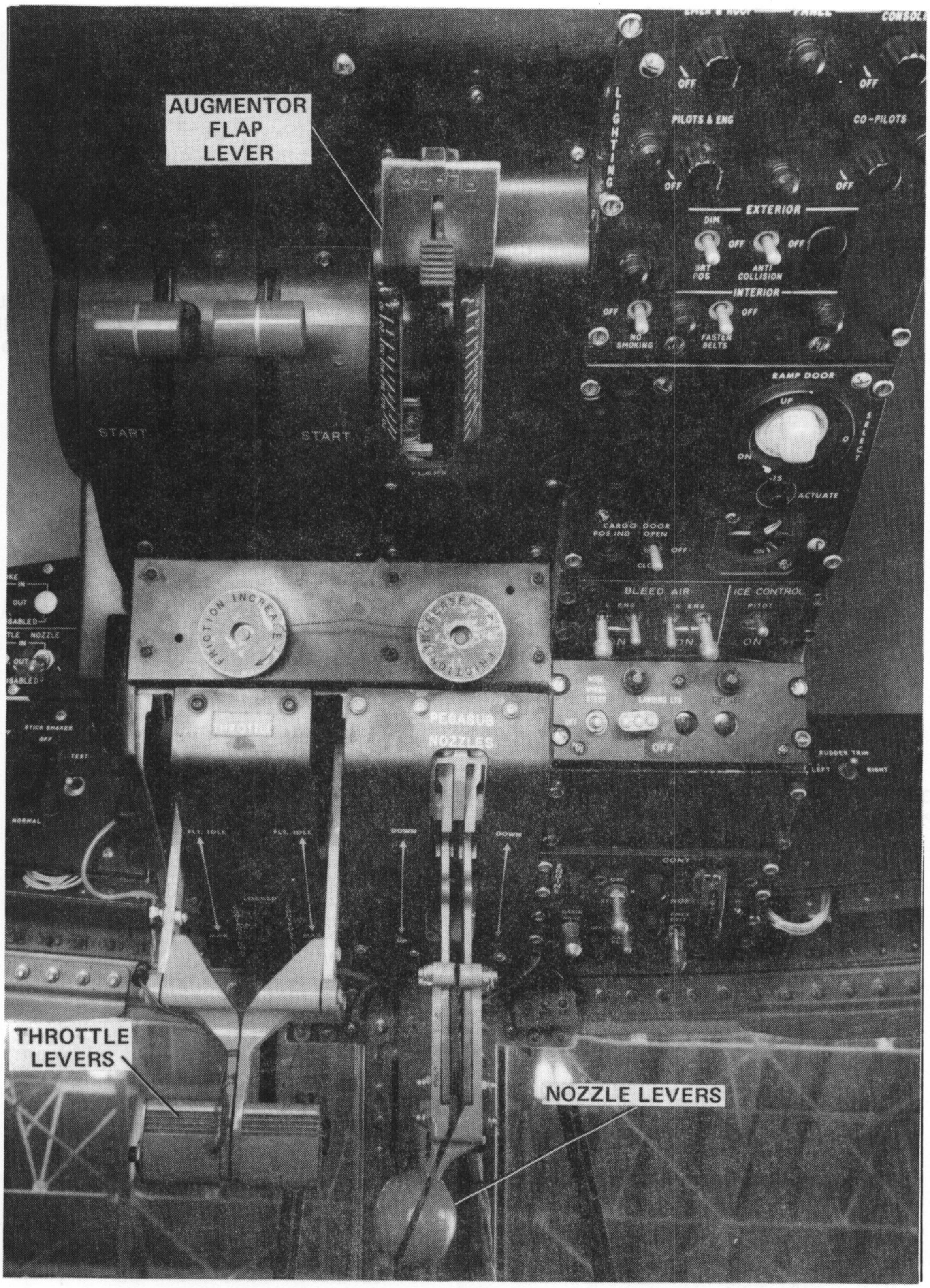
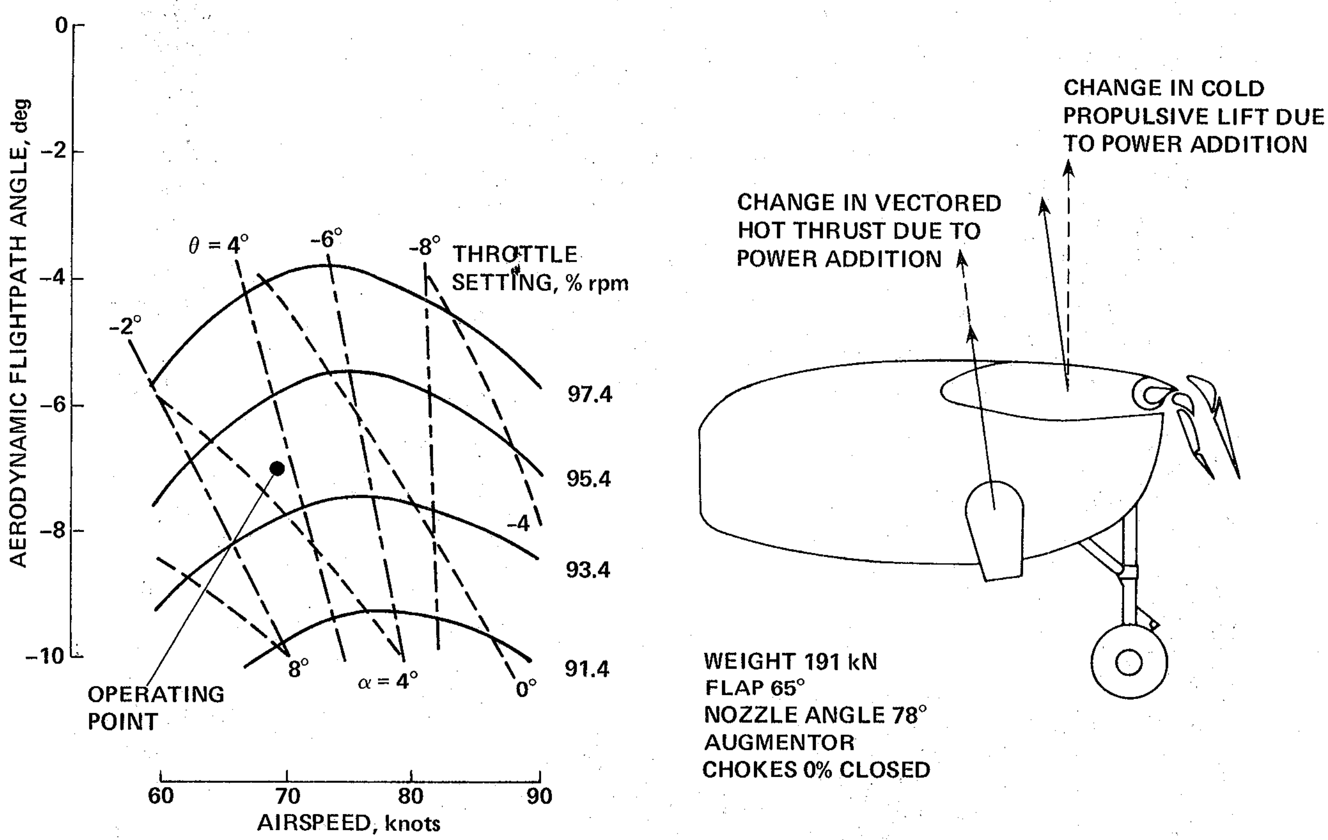
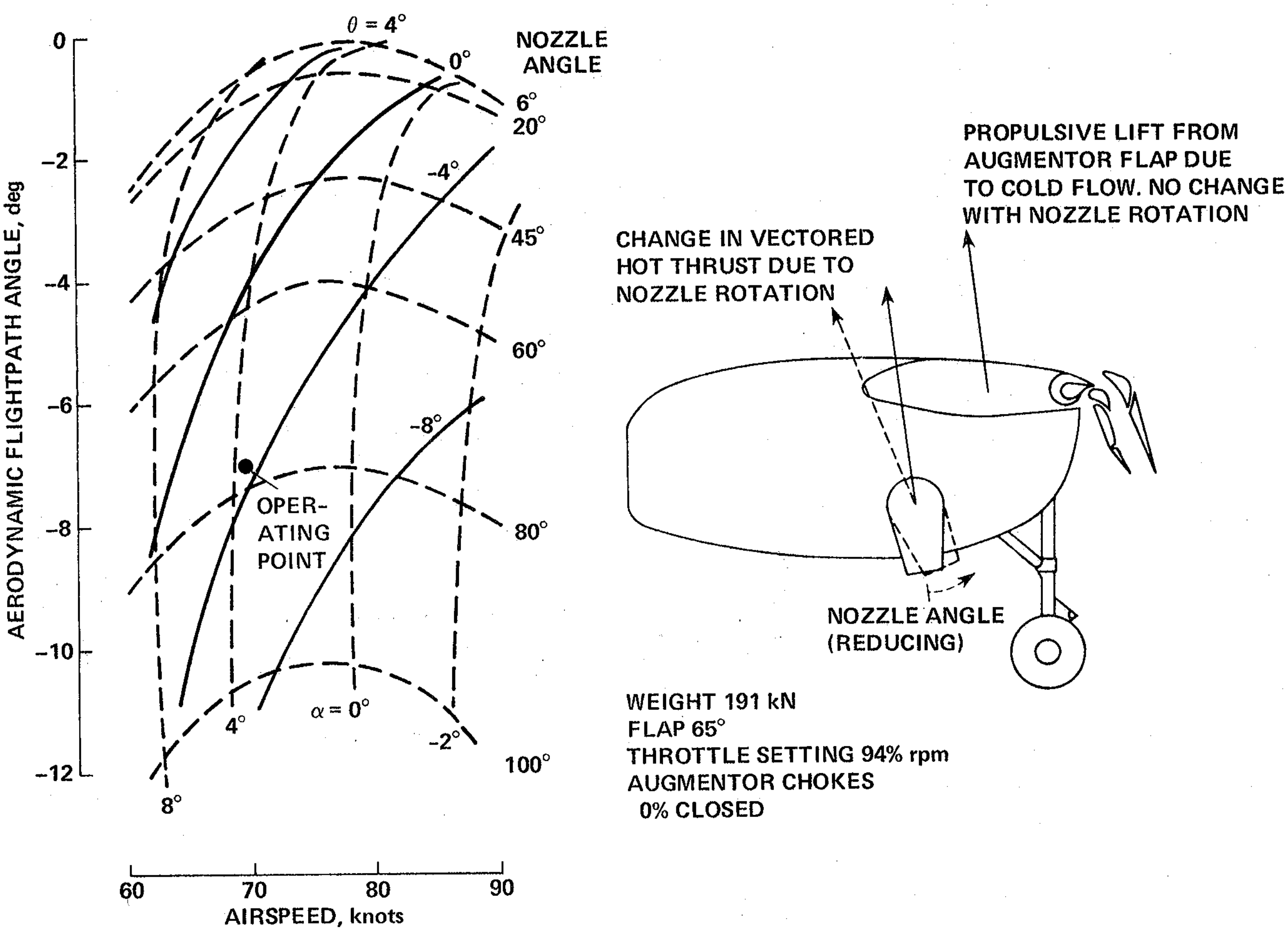


Figure 5.- Overhead propulsion system controls.



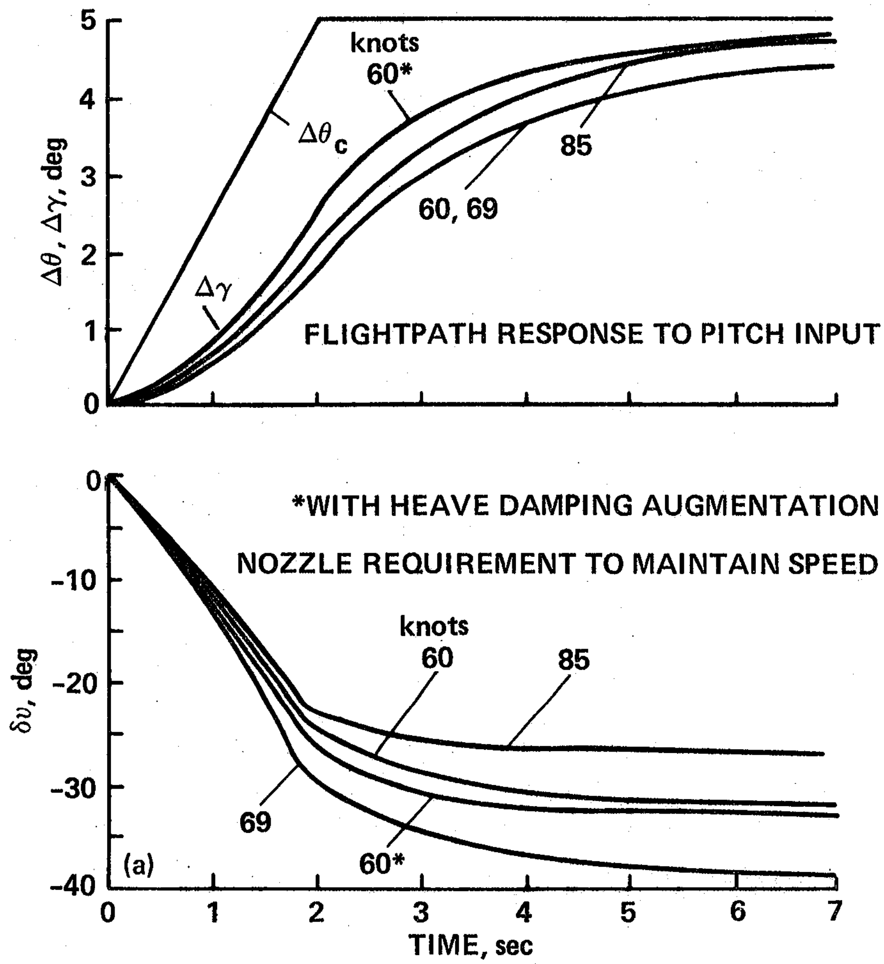
(a) Descent trim conditions, nozzle fixed.

Figure 6.- Flightpath control using throttles or nozzles.



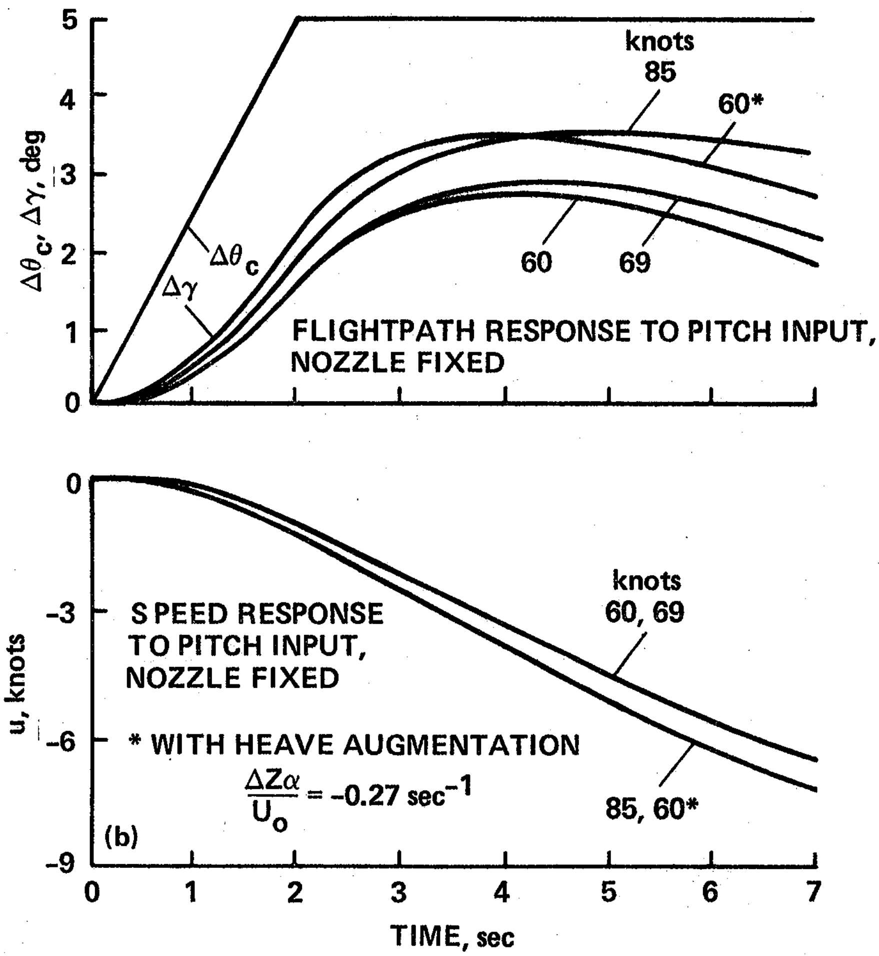
(b) Descent trim conditions, throttle fixed.

Figure 6.- Concluded.



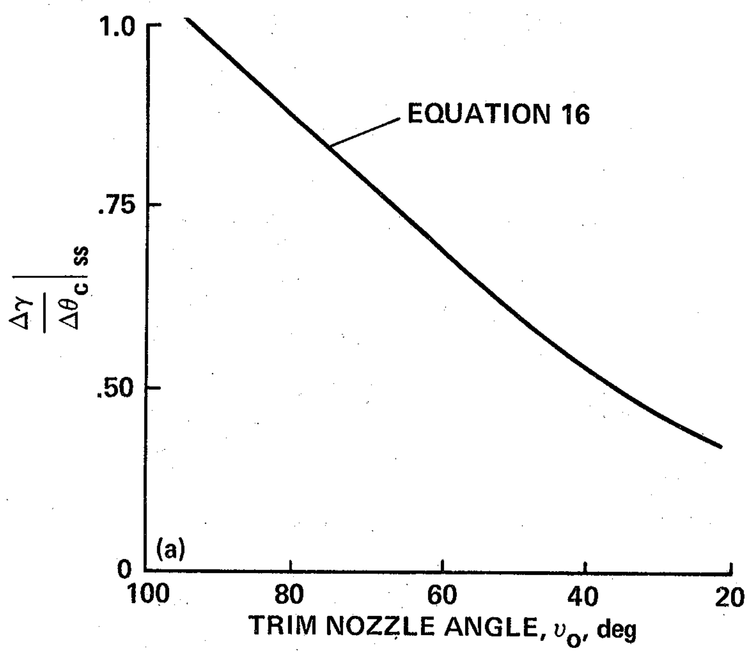
(a) Ideal speed hold.

Figure 7.- Dynamic response to a ramp input in pitch command.



(b) Nozzle fixed.

Figure 7.- Concluded.



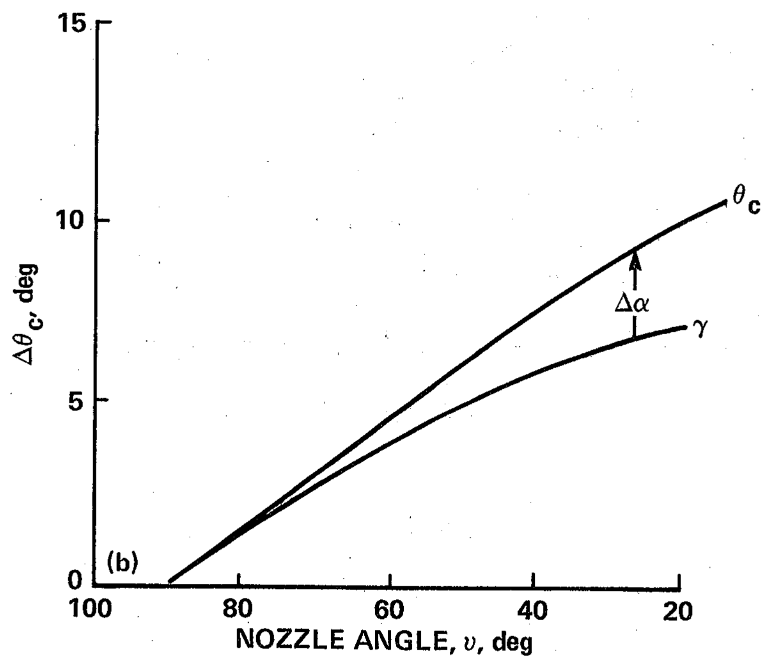


Figure 8.- Long-term reductions in flightpath response for different trim nozzle angles and large control inputs.

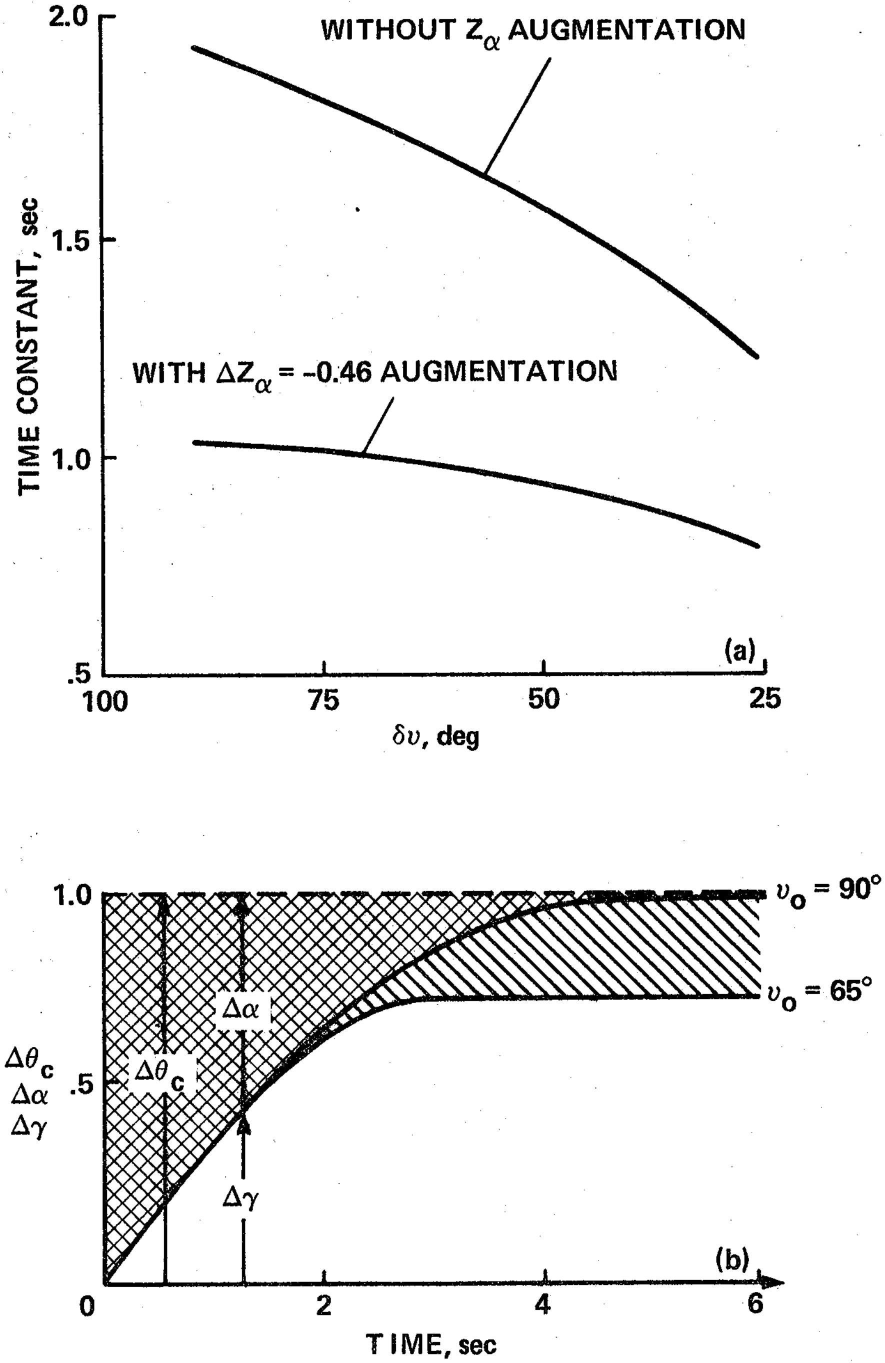


Figure 9.- Short-term effects of different trim nozzle angles.

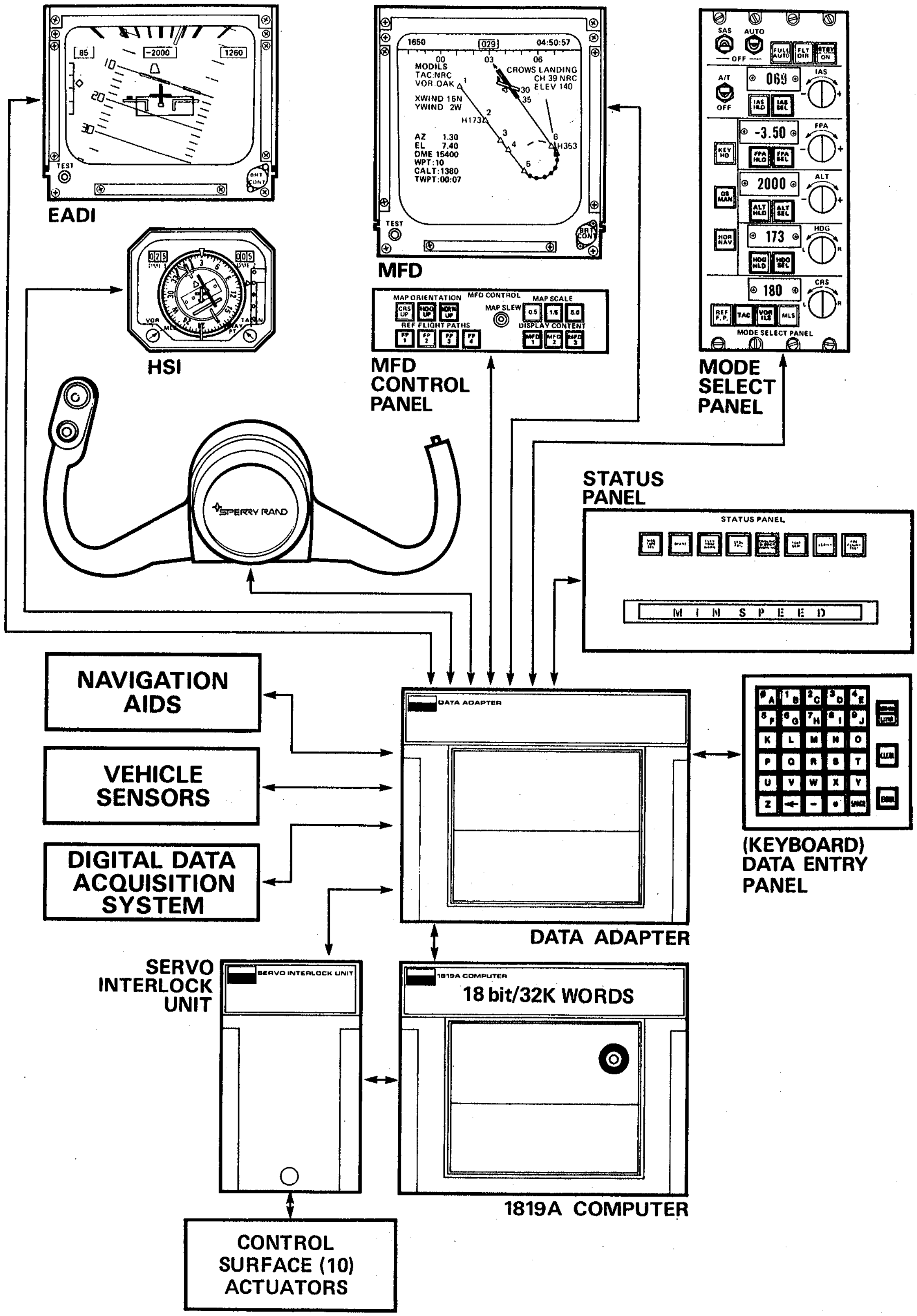
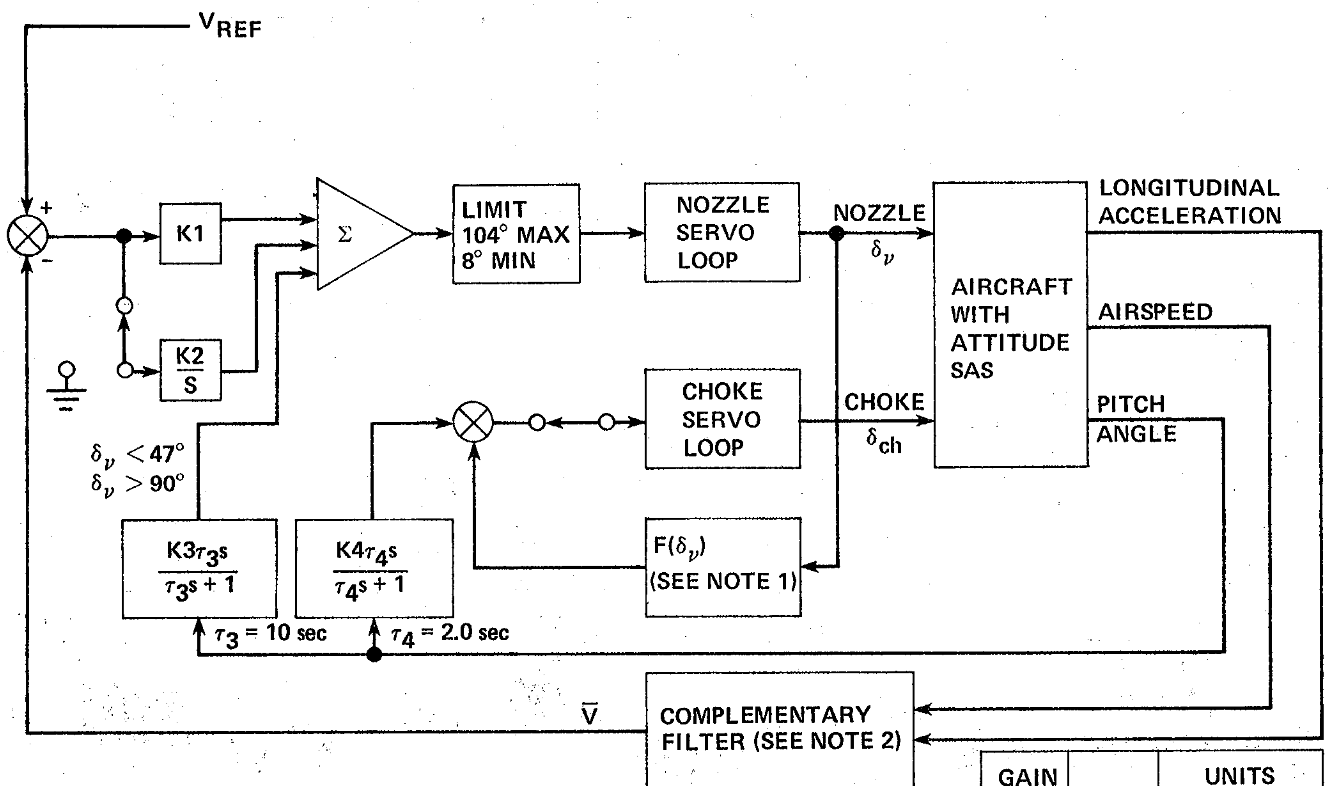


Figure 10.- STOLAND research avionics system.



GAIN		UNITS
K1	-9.2	deg/knot
K2	-1.74	deg/knot-sec
K3	-5.0	deg/deg
K4	-7.5	percent/deg
K5	0.75	percent/deg

NOTES:

1. CHOKE SCHEDULING TO COMPENSATE NOZZLE LIFT LOSS

$$F(\delta_\nu) = \left| \left\{ K5\,(\delta_\nu - \delta_{\nu_{TRIM}}) + 30 \right\} \right|_{\text{max = 40\% closure}}$$

2. AIRSPEED COMPLEMENTARY FILTER

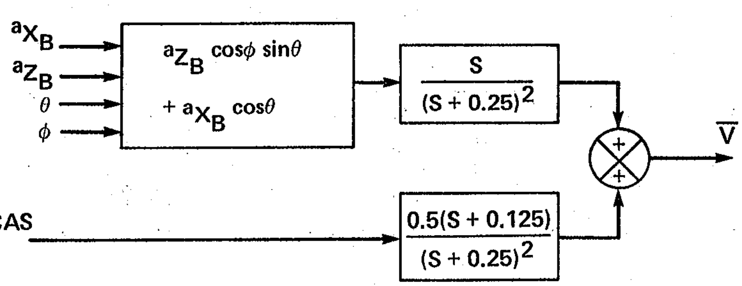


Figure 11.- Speed-hold system details.

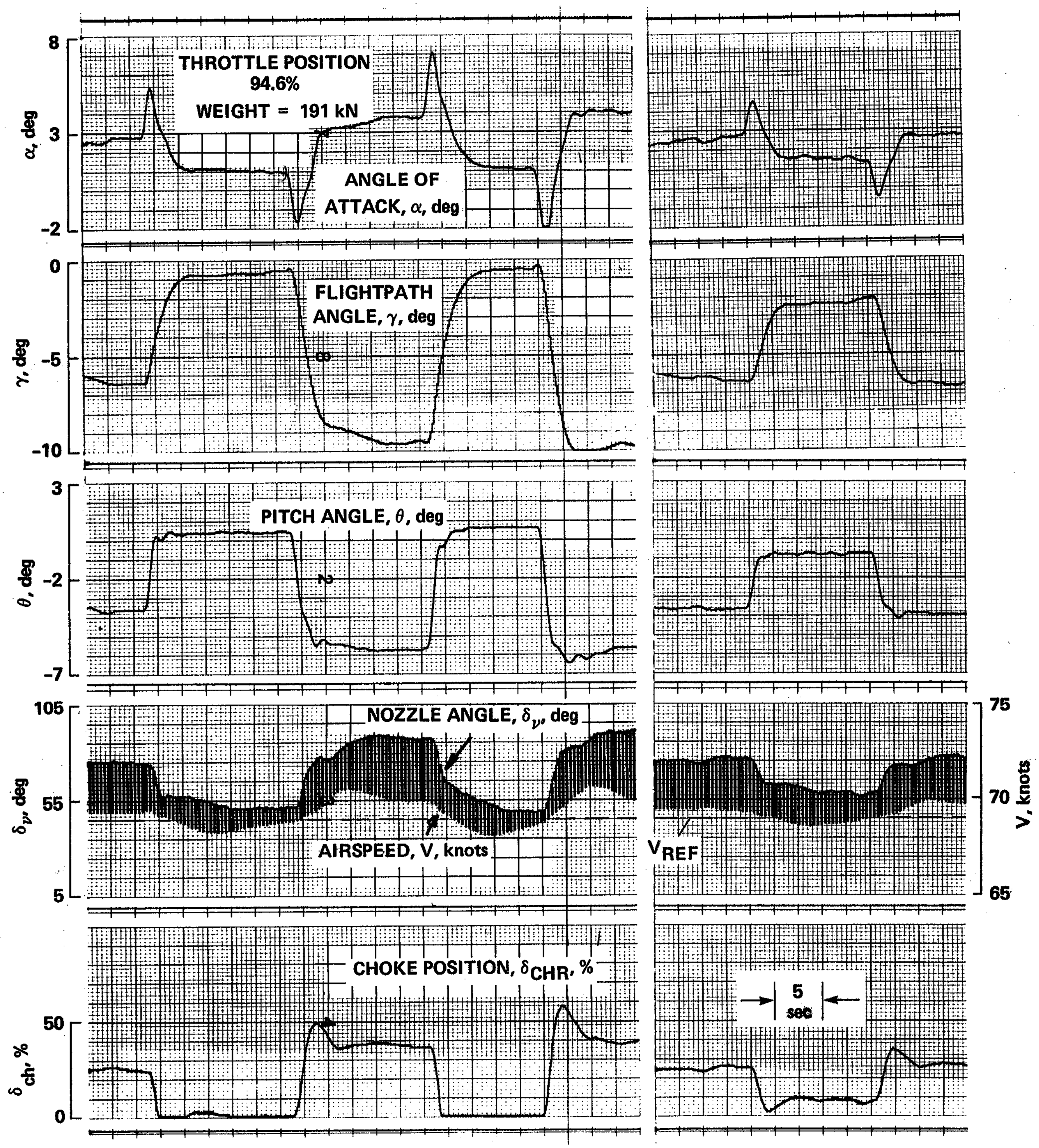


Figure 12.- Aircraft response to pitch control inputs; speed-hold engaged.

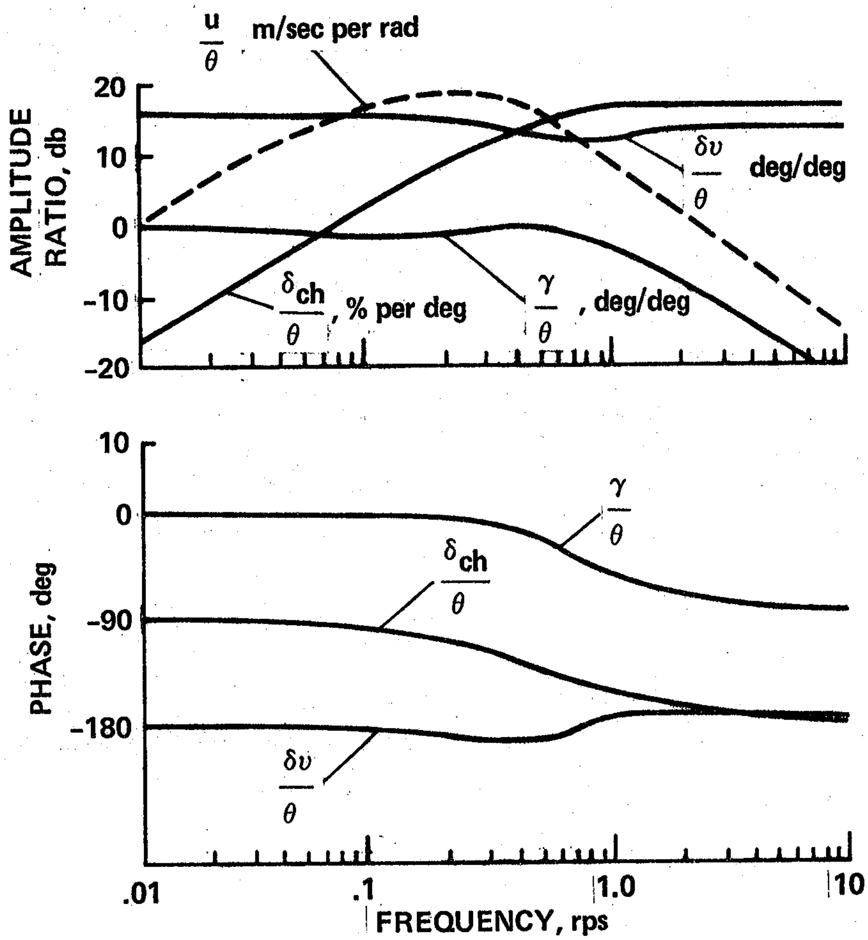


Figure 13.- Frequency response characteristics of the speed-hold system.

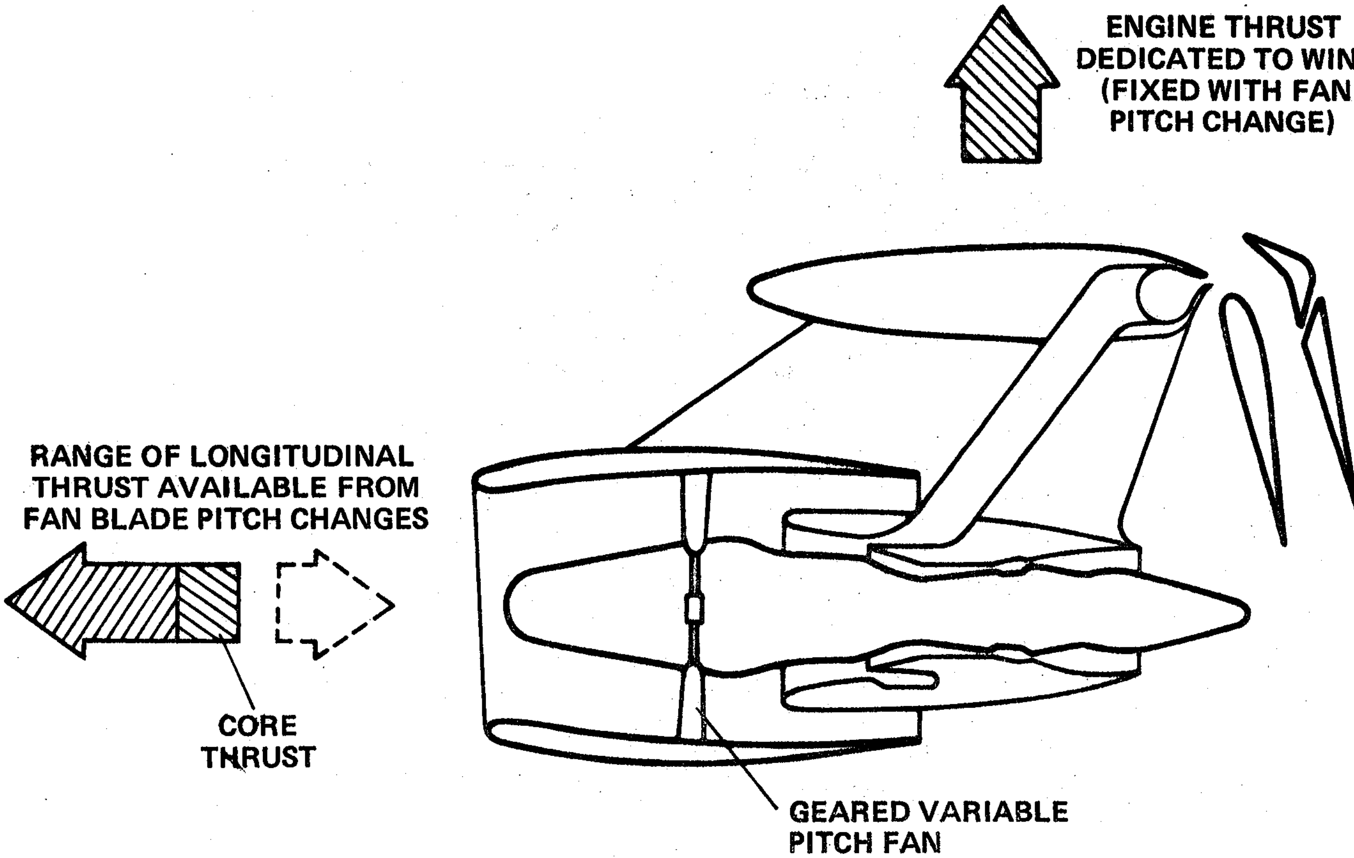
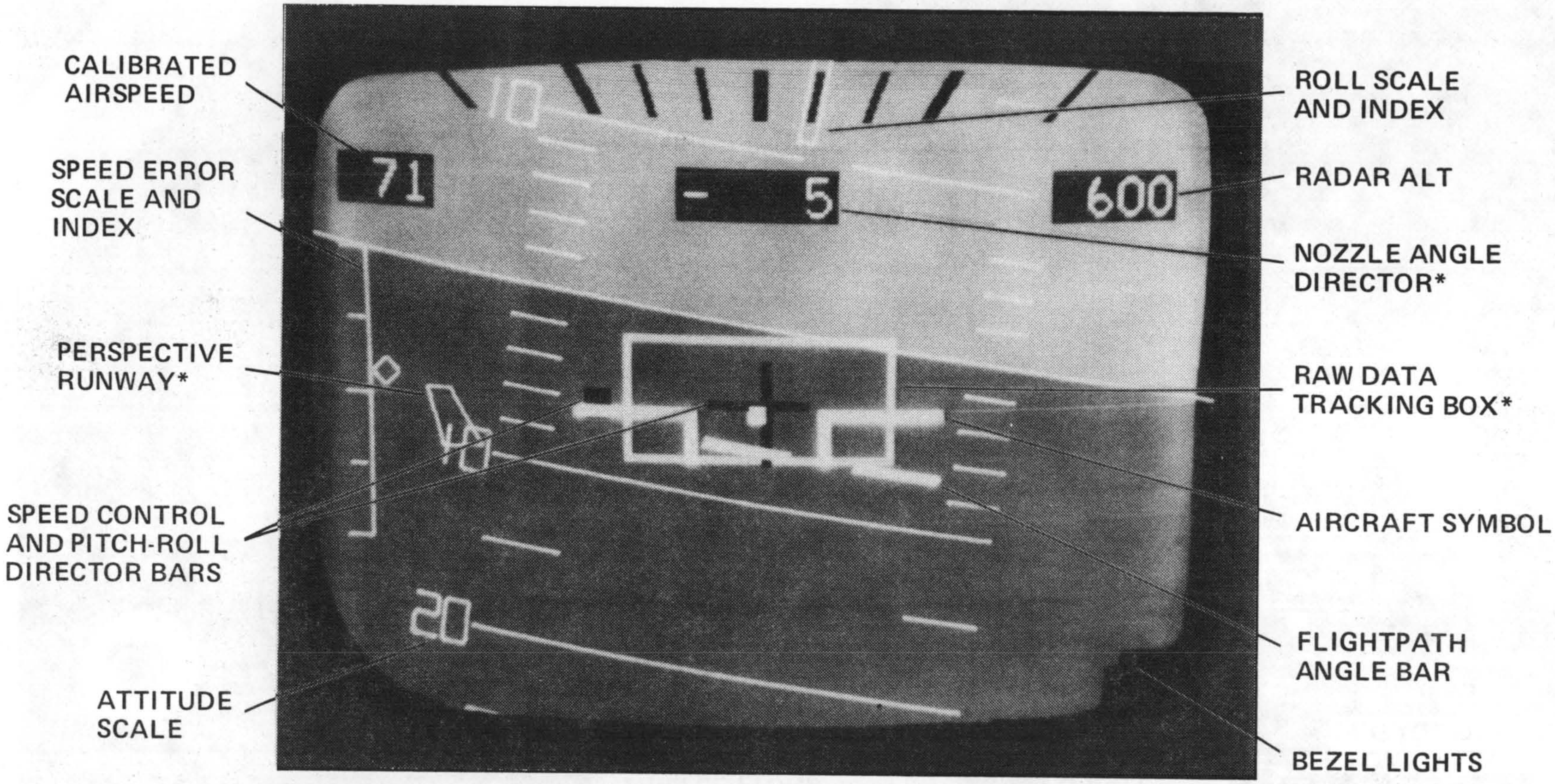


Figure 14.- Possible propulsion system concept providing independent longitudinal thrust control.

Figure 15.- Electric power lever installation.



*DELETED FOR THIS INVESTIGATION

Figure 16.- Electronic attitude director and symbology.

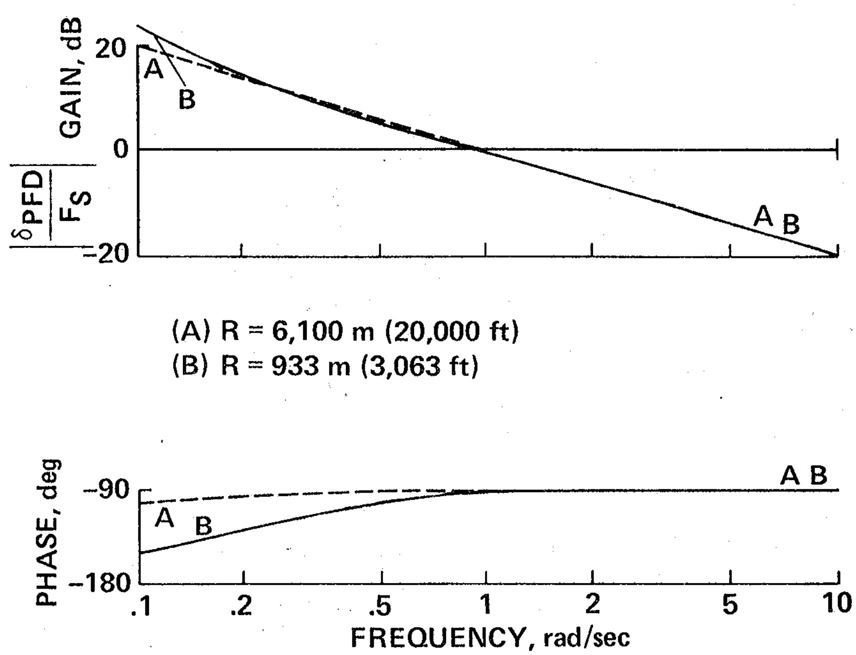


Figure 17.- Dynamic characteristics of the pitch flight director.

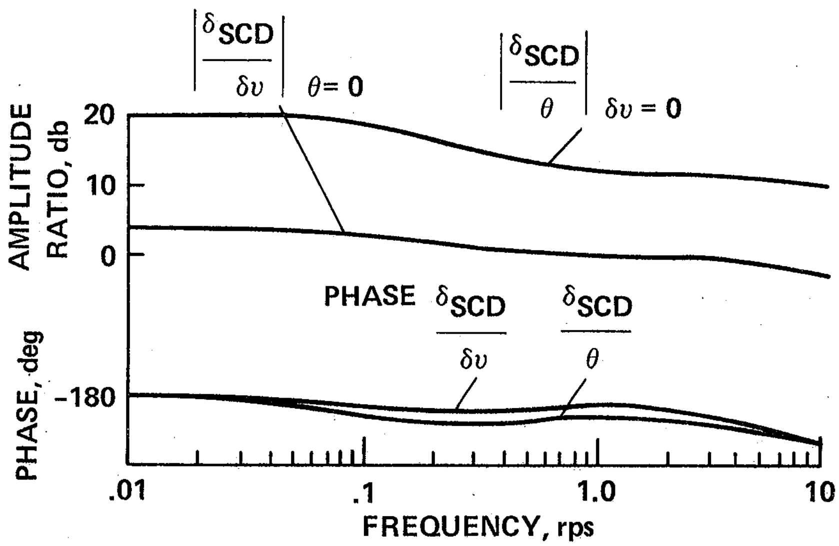


Figure 18.- Dynamic characteristics of the speed-control director.

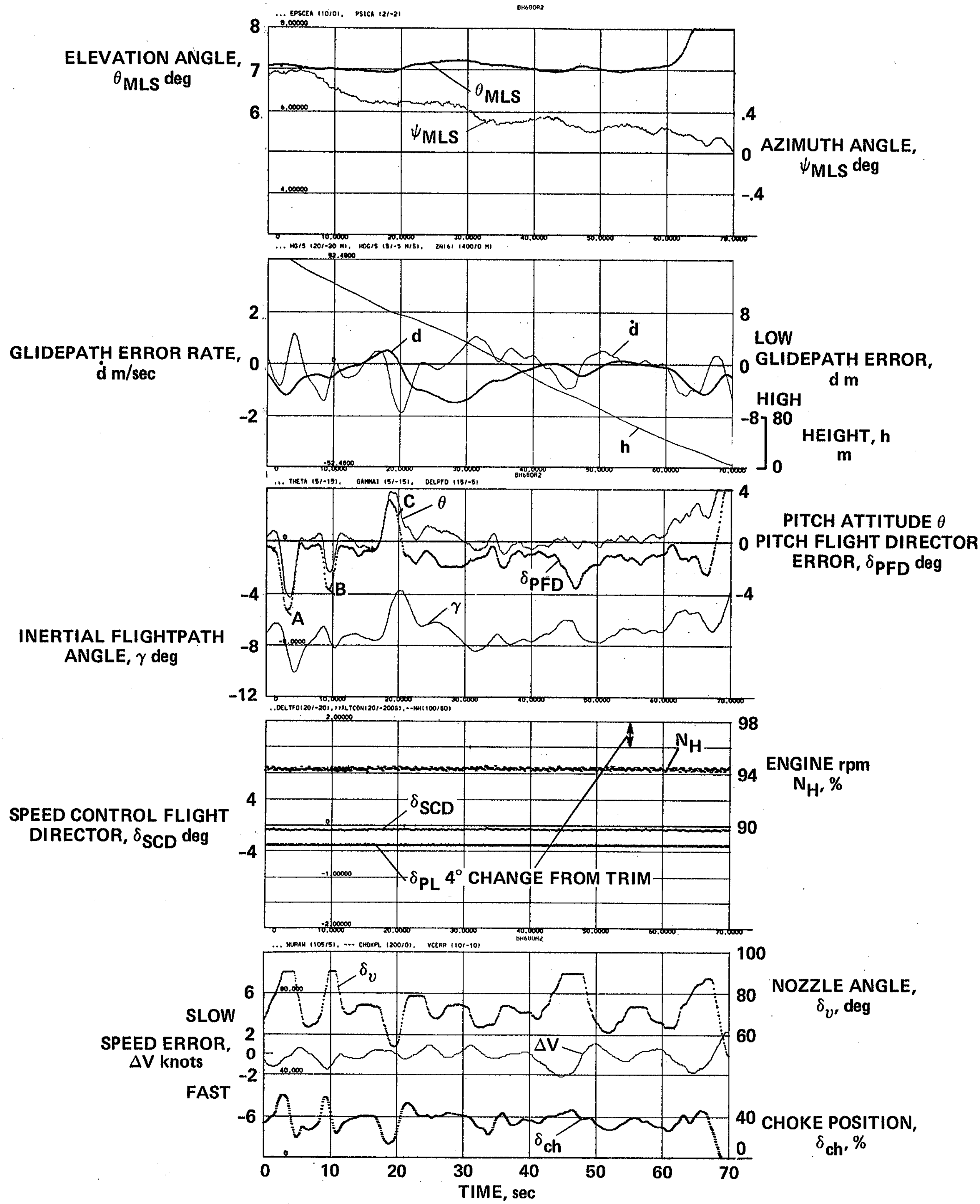
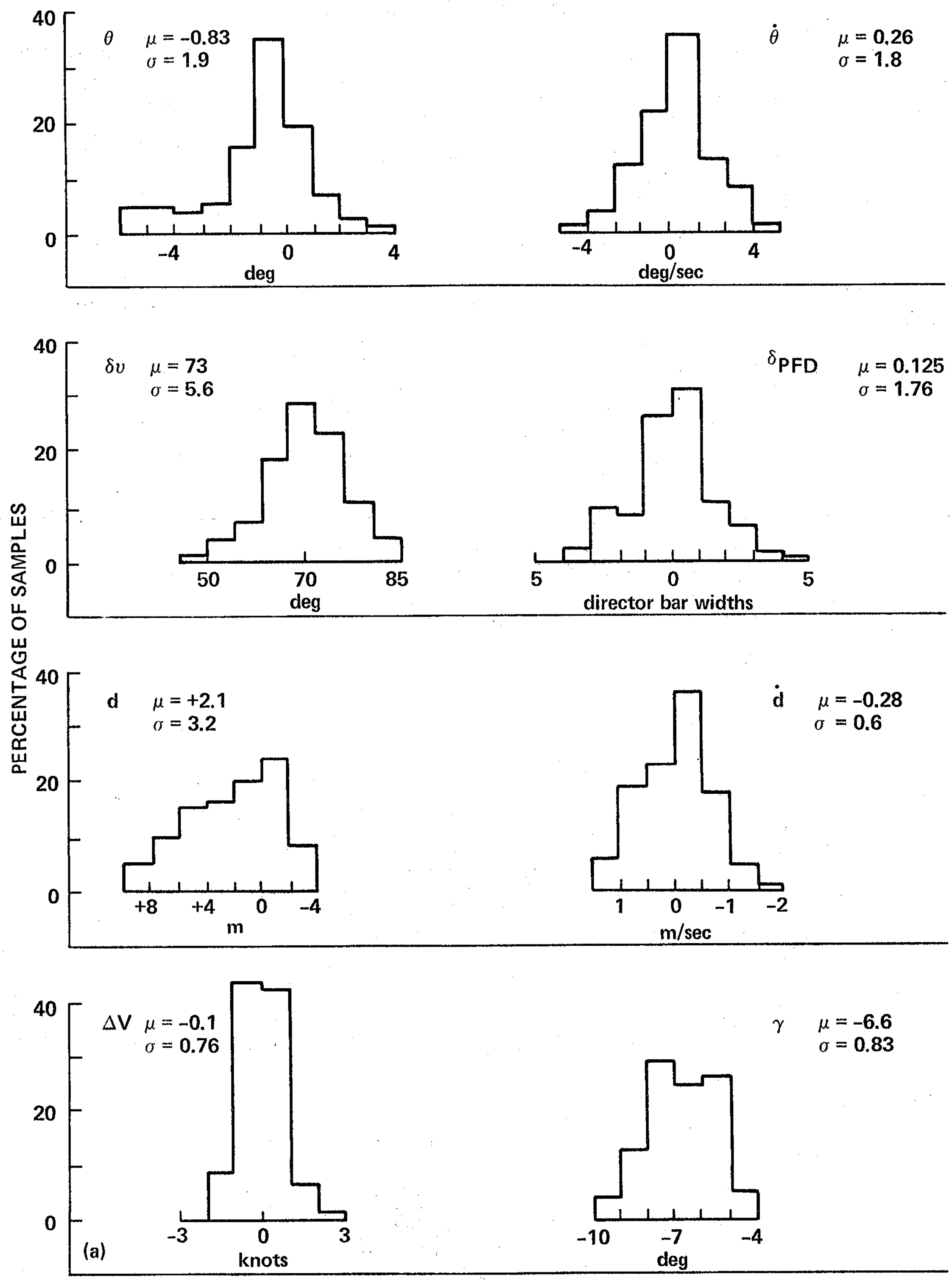
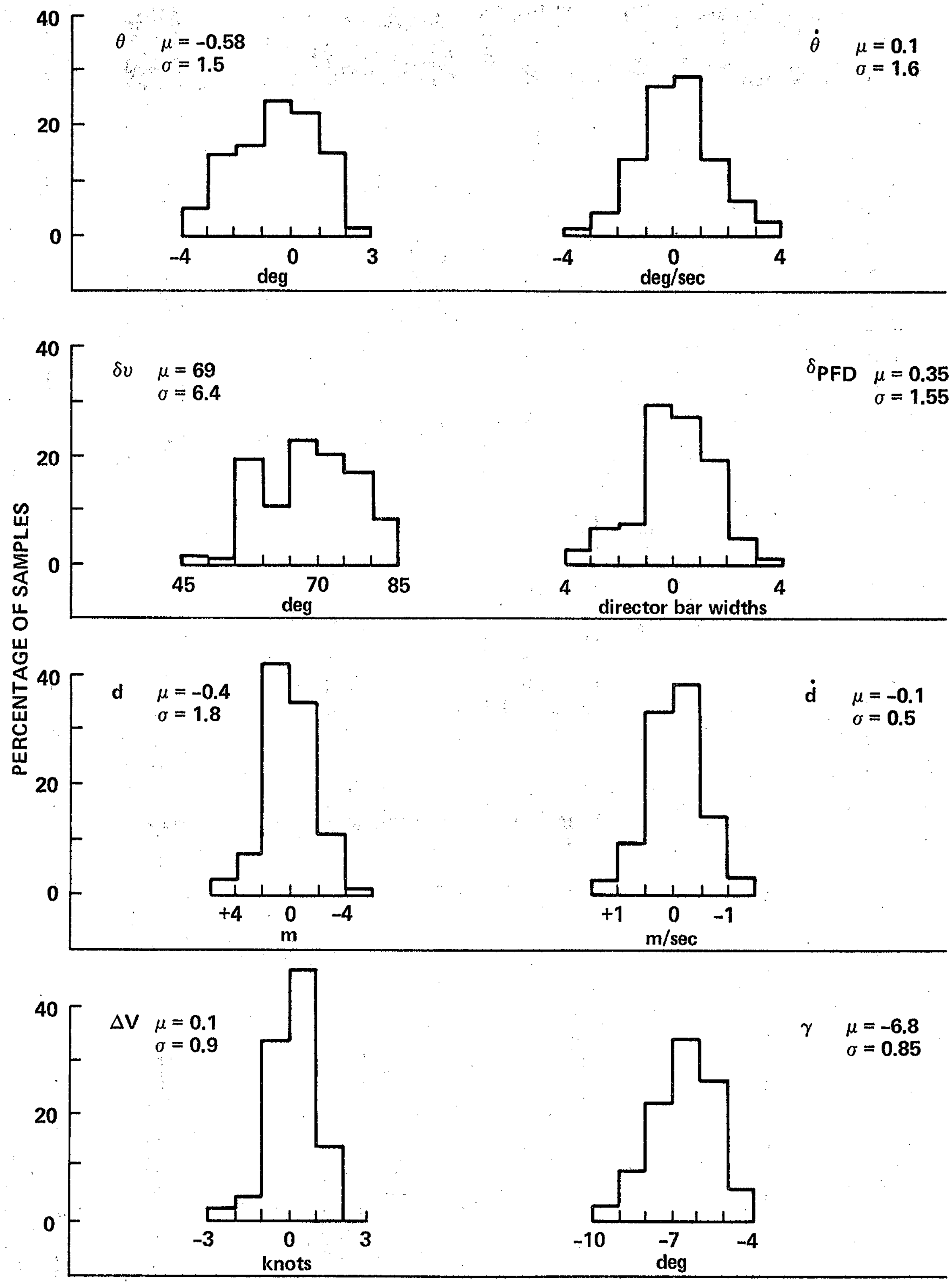


Figure 19.- Approach time history - configuration C_{11} (automatic speed control; pitch and roll flight directors).



(a) Altitude band 210-110 m (183 sec of data from seven approaches).

Figure 20.- Performance and control utilization histograms, configuration C_{11} (automatic speed control; pitch and roll flight directors).



(b) Altitude band 110-30.5 m (127 sec of data from seven approaches).

Figure 20.- Concluded.

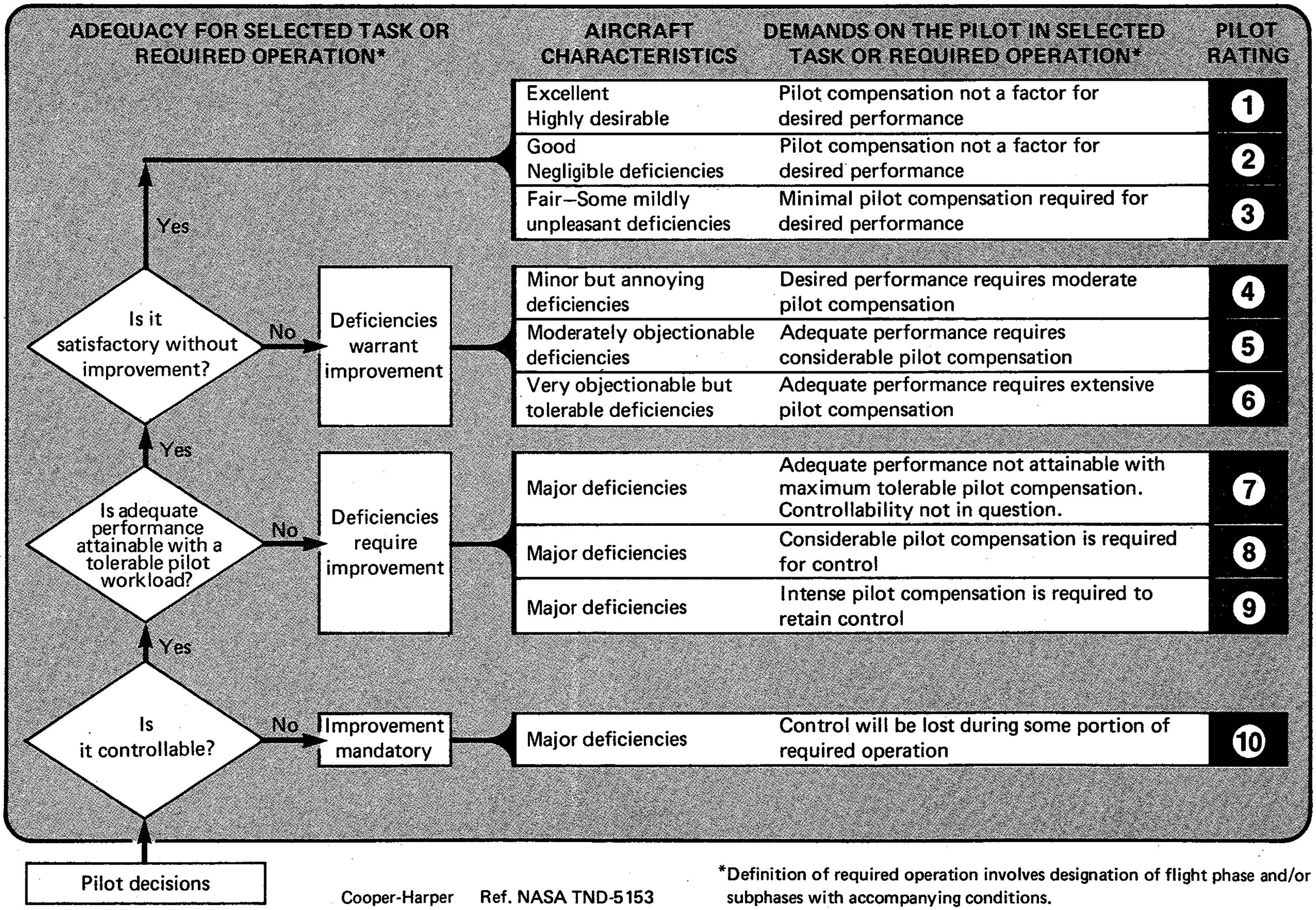


Figure 21.- Pilot rating scale.

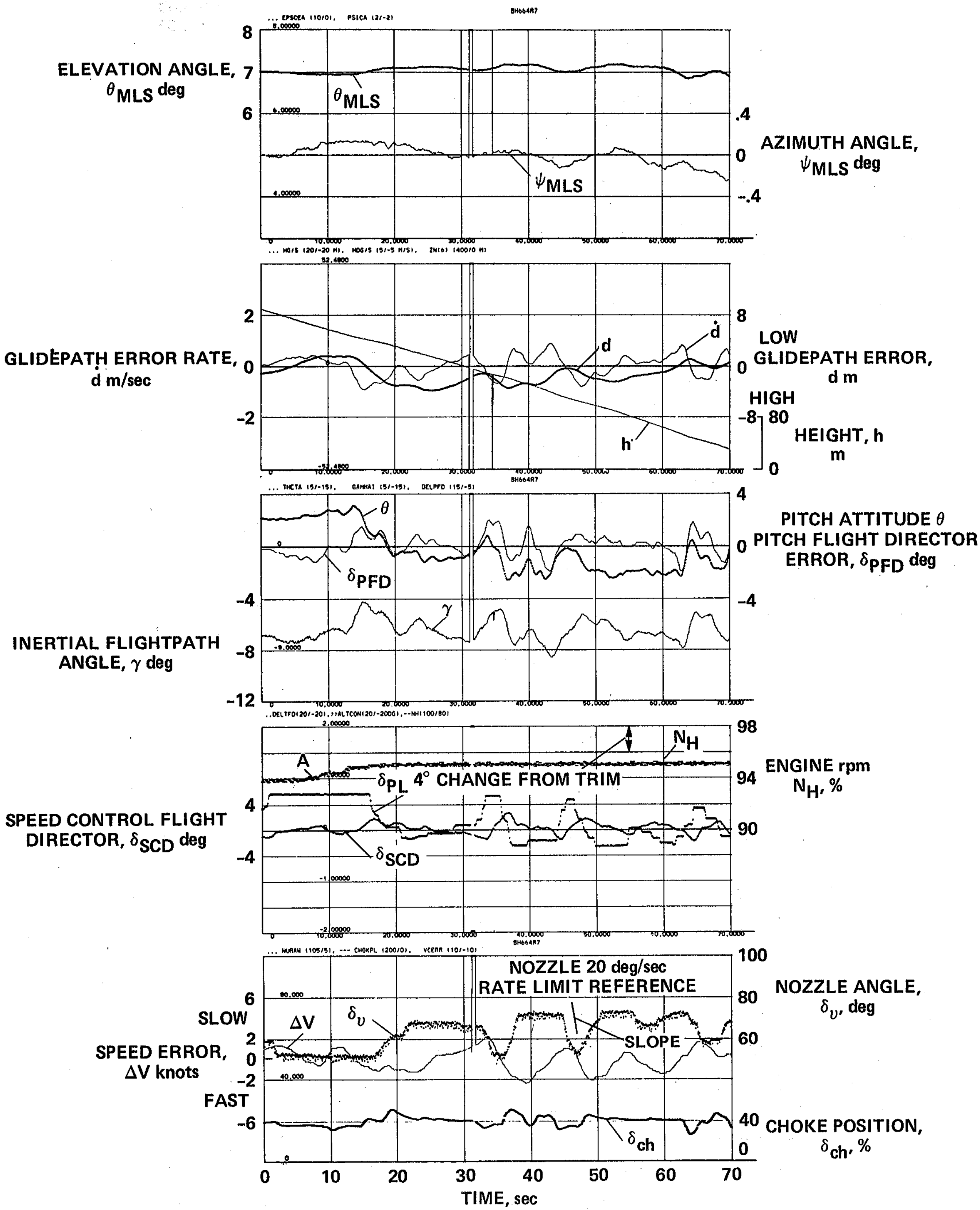
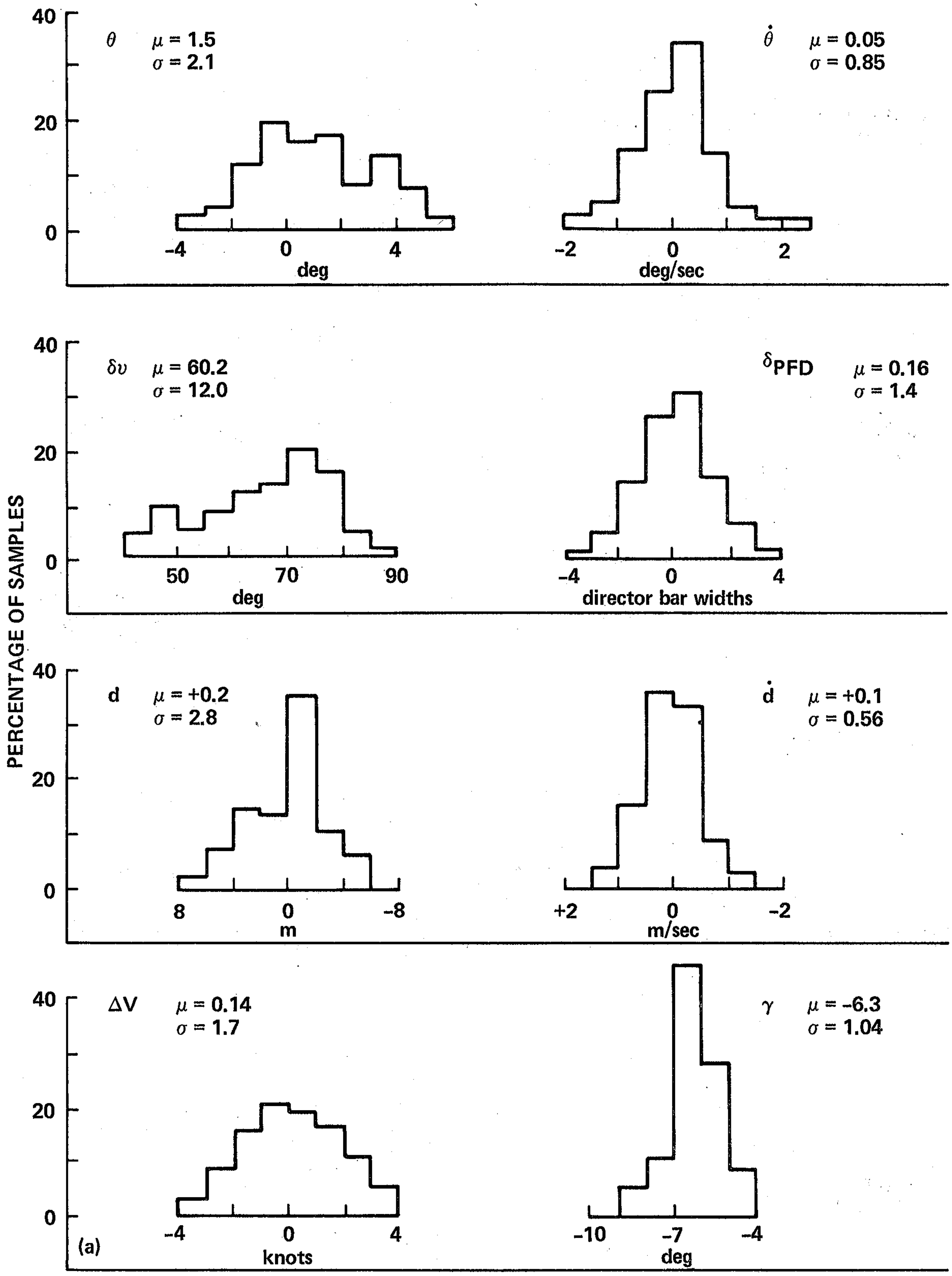
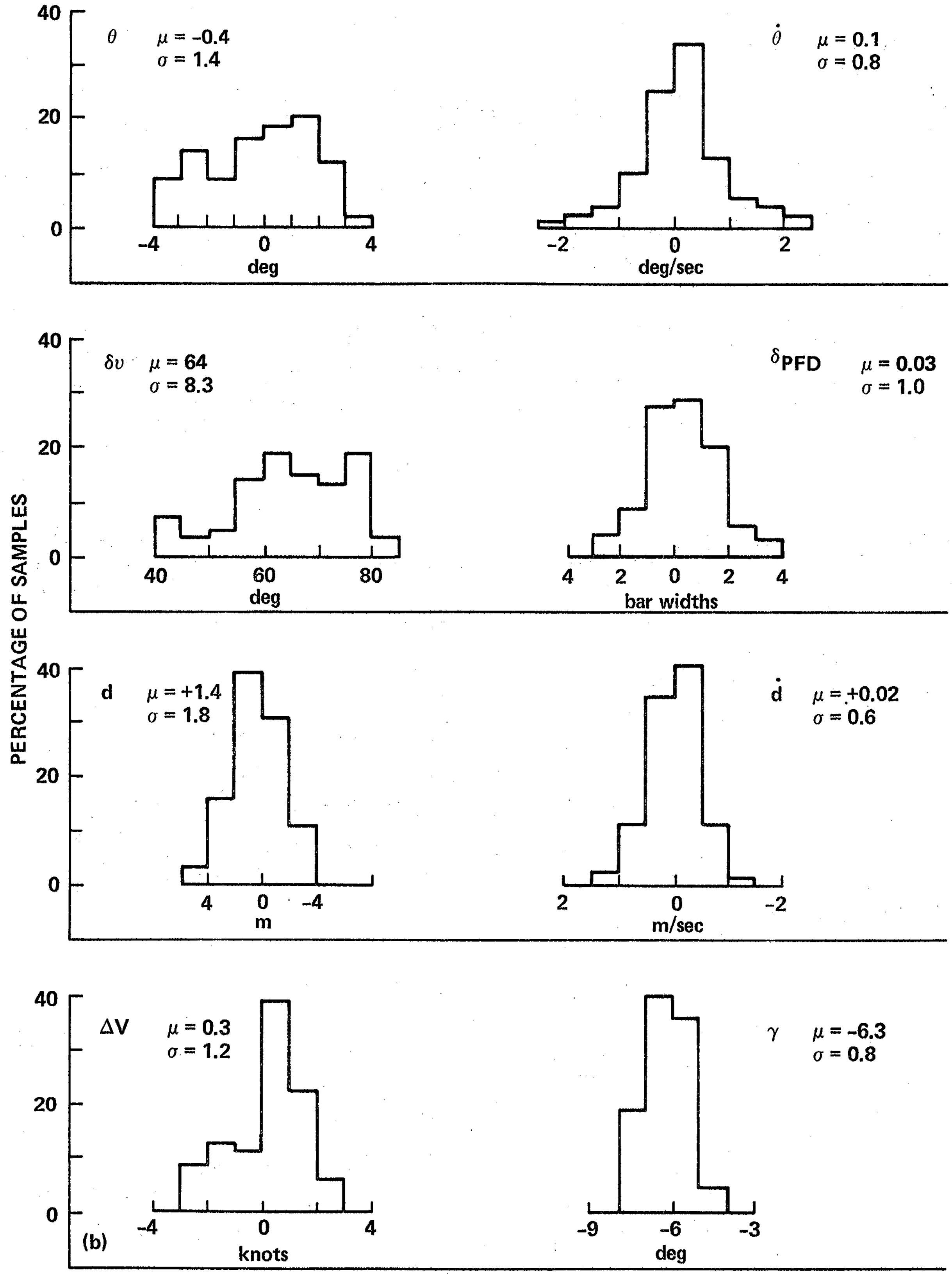


Figure 22.- Approach time-history - configuration C_{21} (proportional control of nozzles with electric power lever; pitch, roll, and speed-control directors).



(a) Altitude band 210-110 m (197 sec of data from seven approaches).

Figure 23.- Performance and control utilization histograms - configuration C_{21} (proportional control of nozzles with electric power lever; pitch, roll, and speed control directors).



(b) Altitude band 110-30.5 m (148 sec of data from seven approaches).

Figure 23.- Concluded.

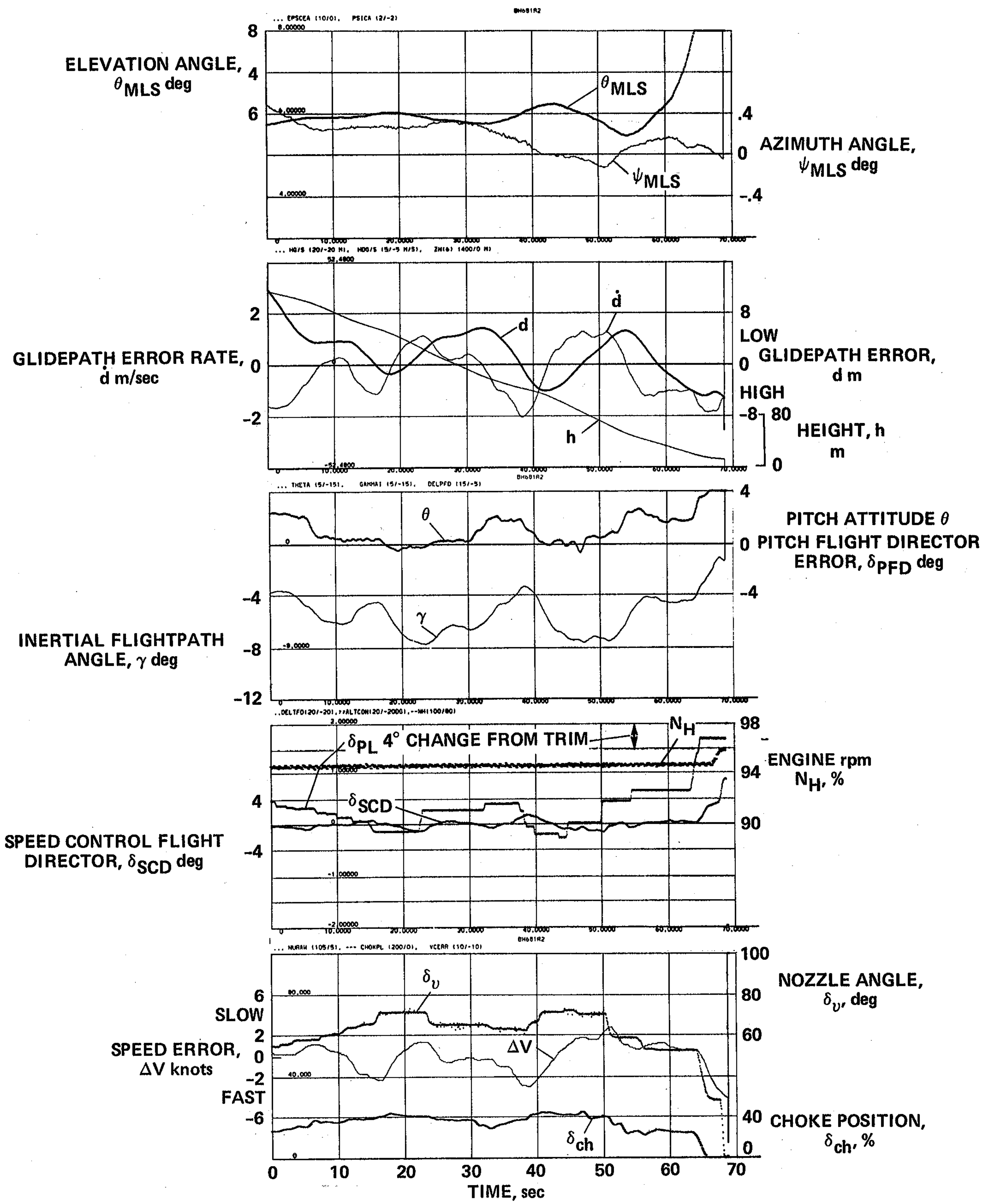


Figure 24.- Approach time history - configuration C_{22} (proportional control of nozzles with electric power lever; speed-control director alone).

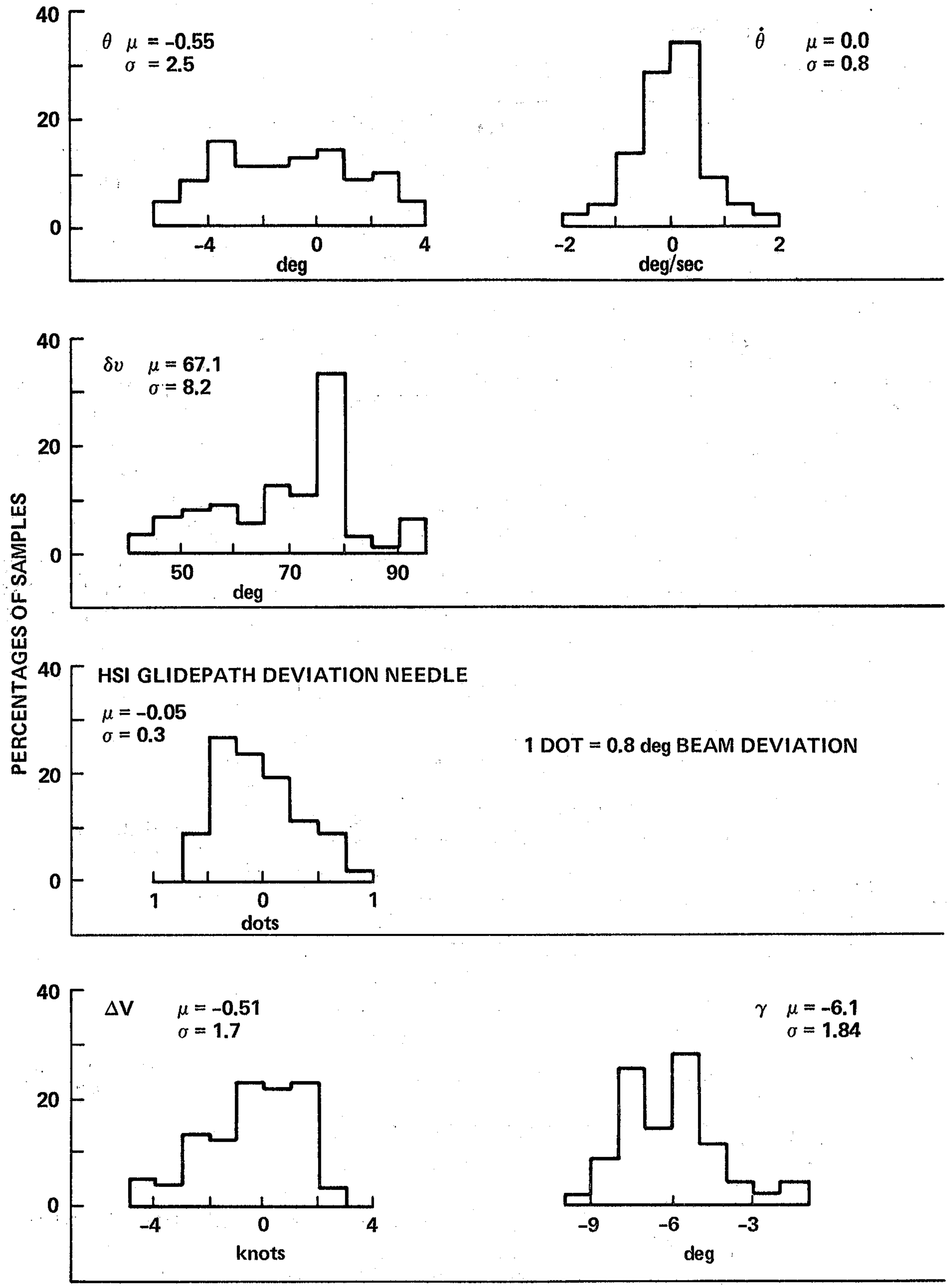


Figure 25.- Performance and control utilization histograms - configuration C_{22} (proportional control of nozzles with electric power lever; speed-control director alone).

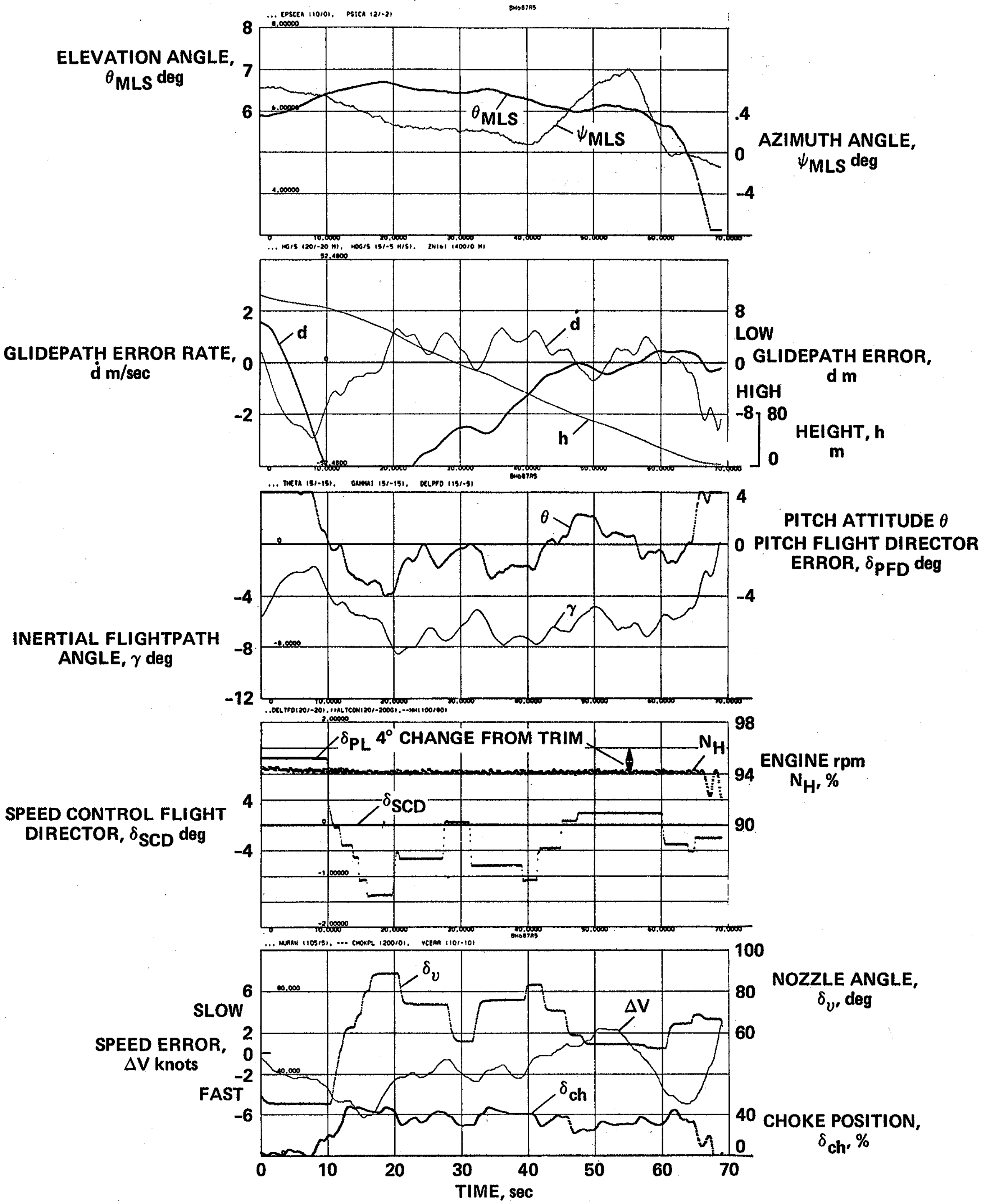


Figure 26.- Approach time history - configuration C_{23} (proportional control of nozzles with electric power lever; all director elements removed).

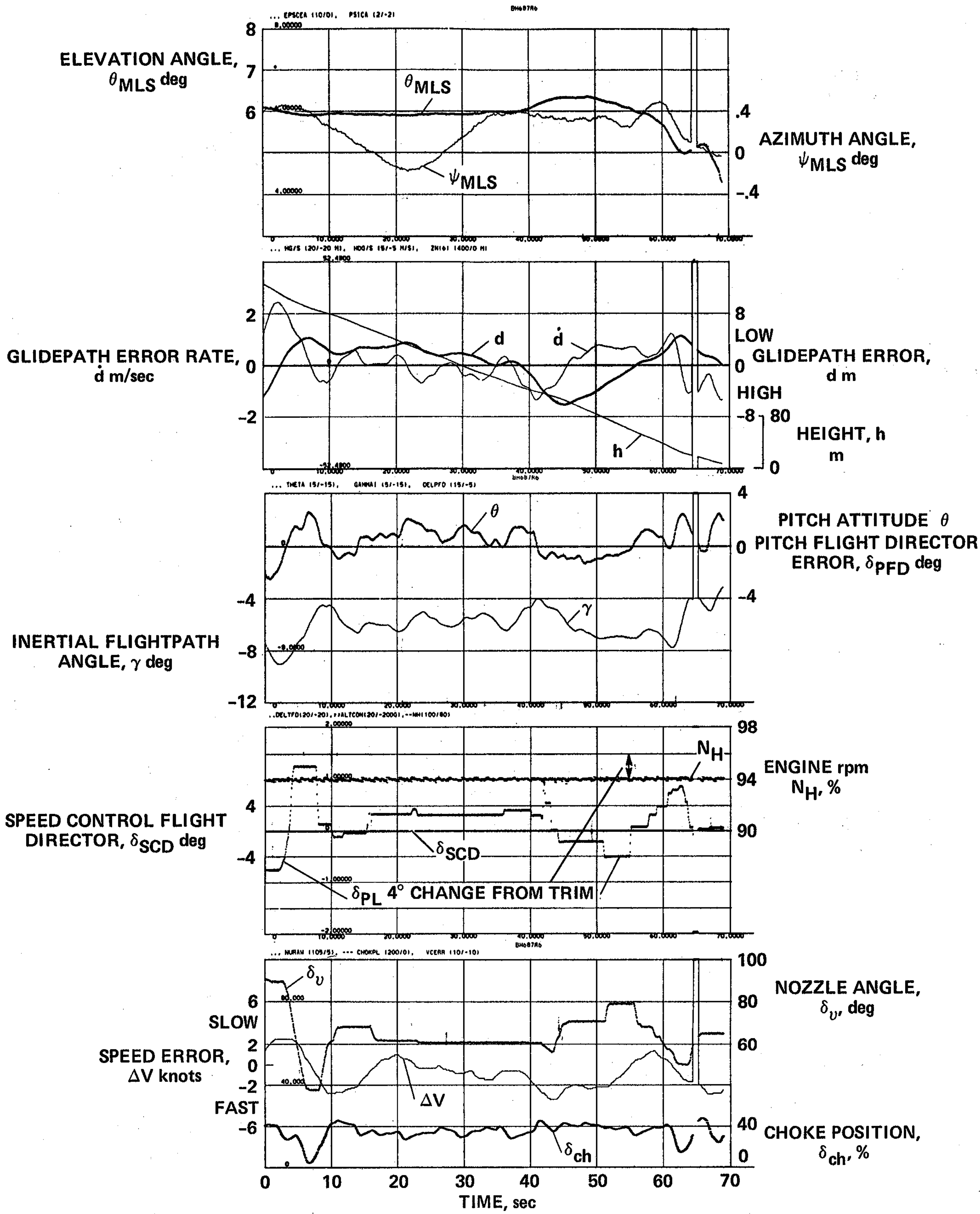


Figure 27.- Approach time history - configuration C_{23} (proportional control of nozzles with electric power lever; all director elements removed).

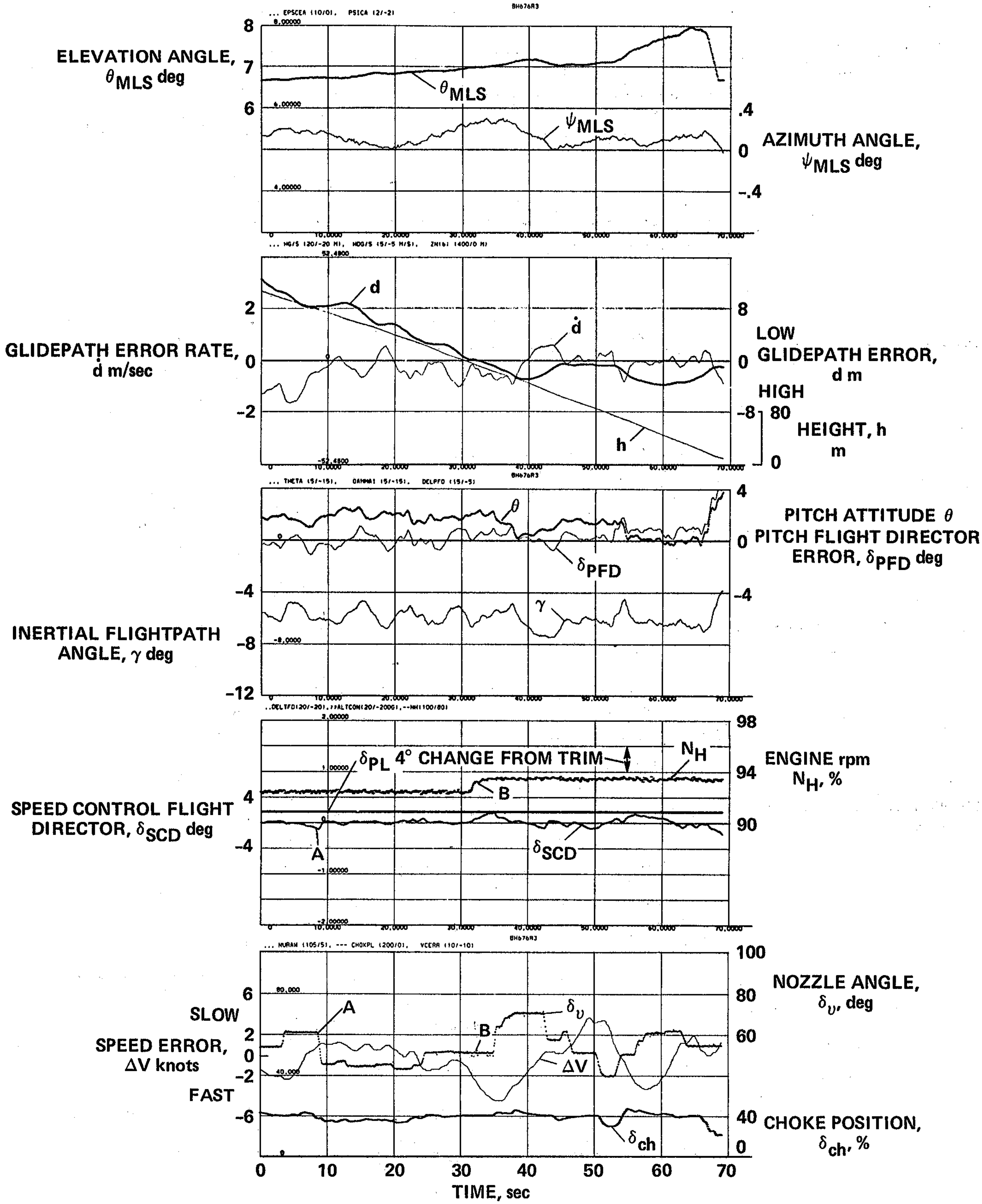
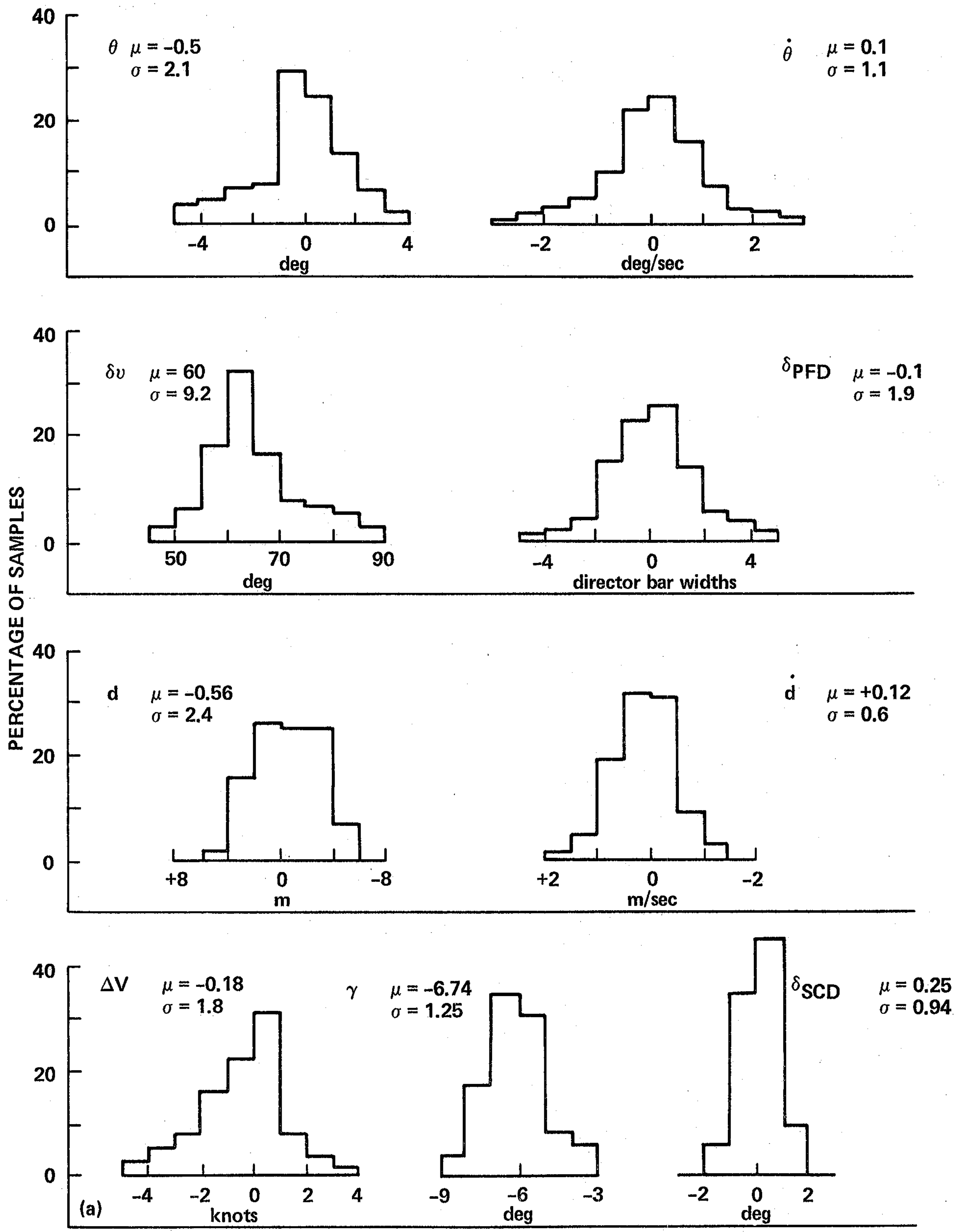
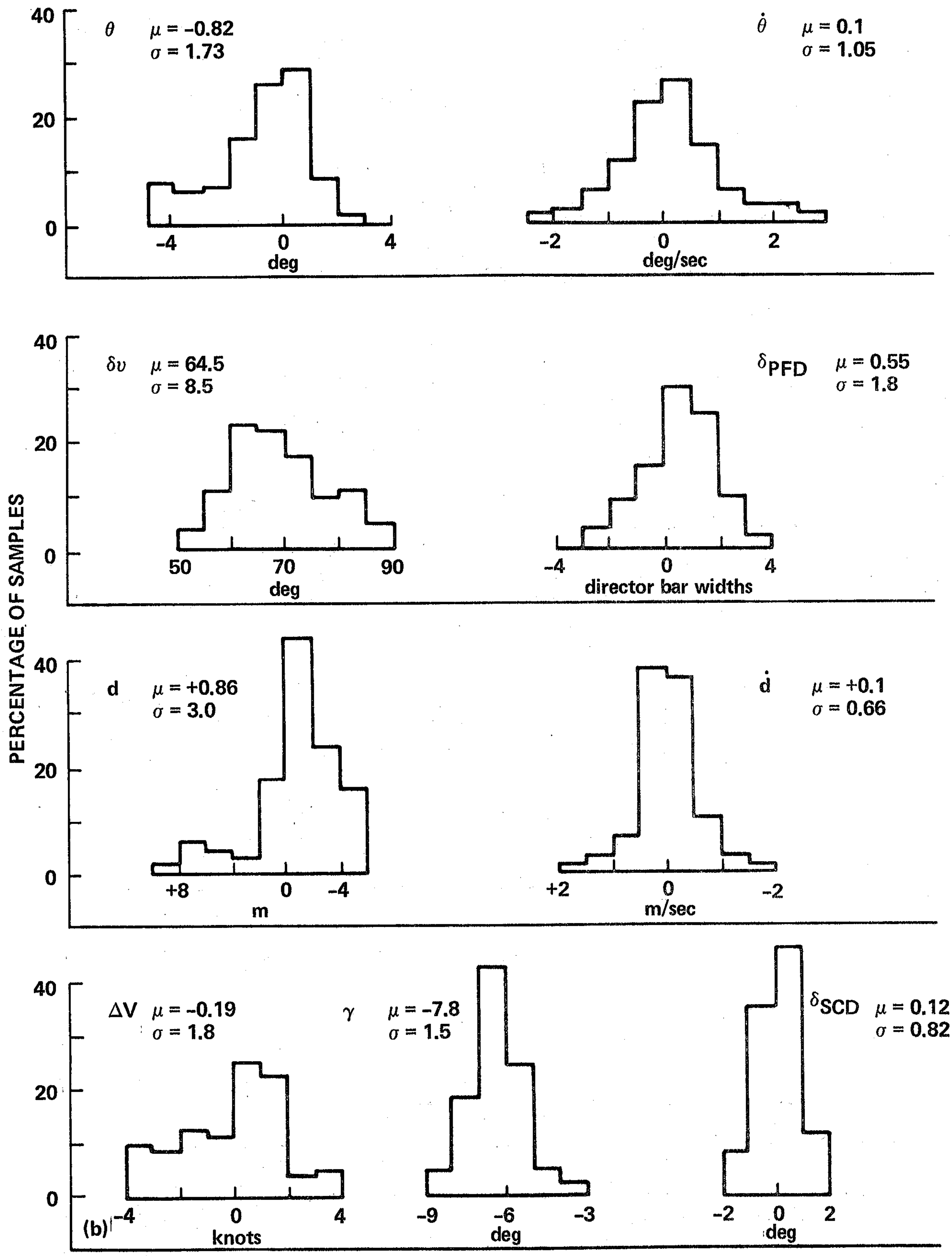


Figure 28.- Approach time history - configuration C_{31} (proportional control of nozzles with overhead controls; pitch, roll, and speed-control directors).



(a) Altitude band 210-110 m (147 sec of data from five approaches).

Figure 29.- Performance and control utilization histograms - configuration C_{31} (proportional control of nozzles with overhead controls; pitch, roll, and speed-control directors).



(b) Altitude band 110-30.5 m (98 sec of data from five approaches).

Figure 29.- Concluded.

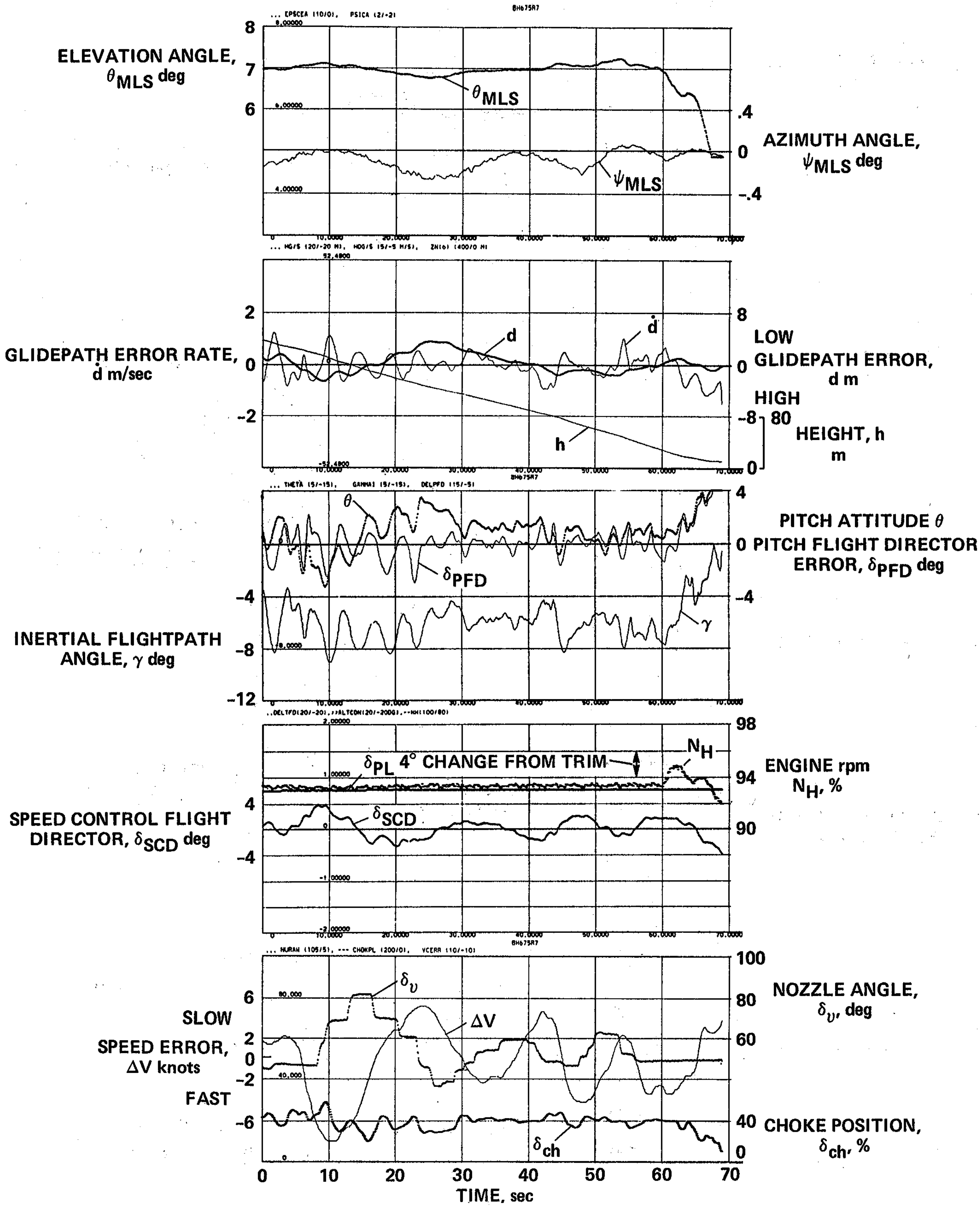


Figure 30.- Approach time history - configuration C_{41} (rate control of nozzles with electric rate switch; pitch, roll, and speed-control directors).

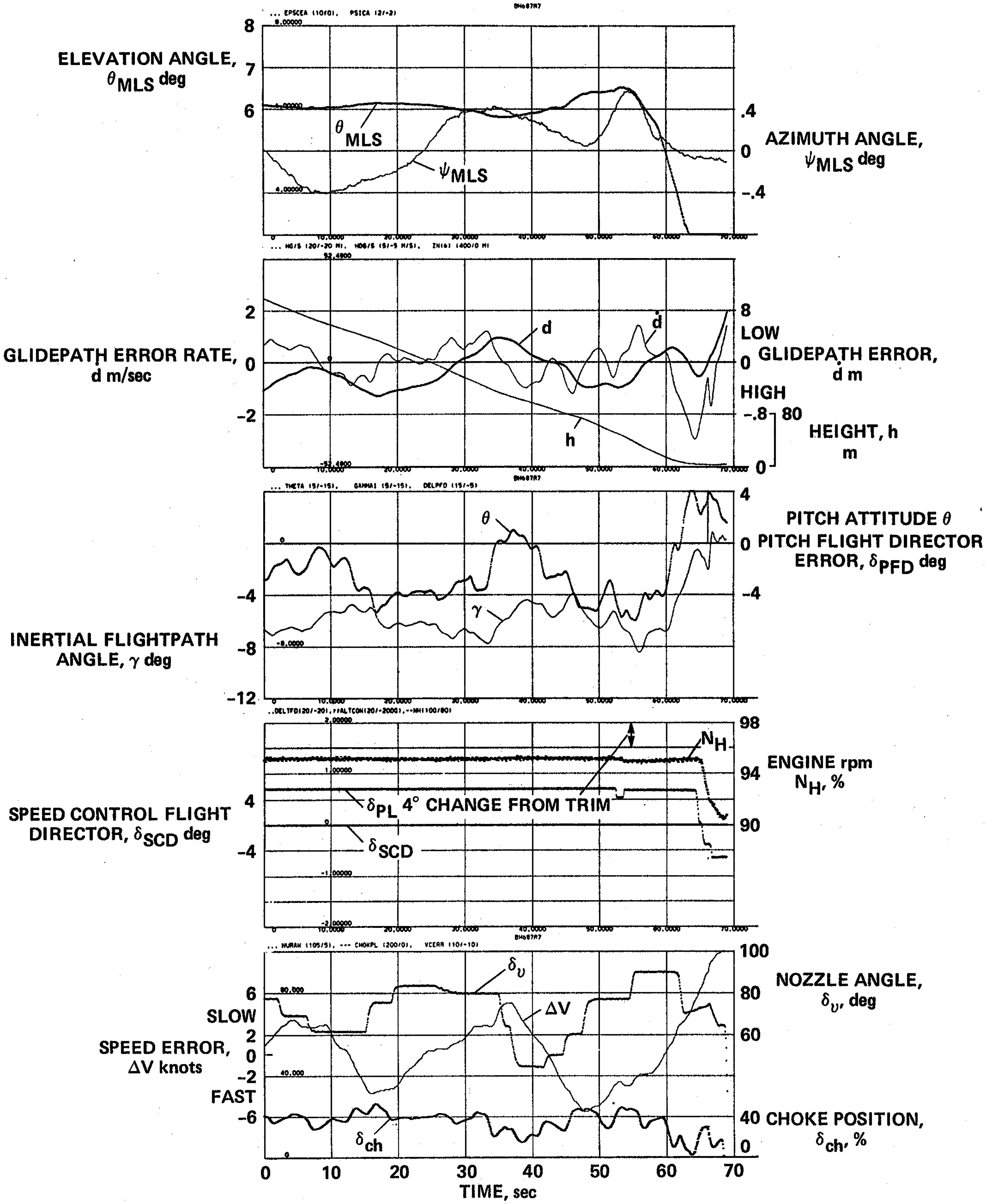


Figure 31.- Approach time history - configuration C_{43} (rate control of nozzles with electric rate switch; all director elements removed).

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16. Abstract

The essential features of using pitch attitude for glidepath control in conjunction with longitudinal thrust modulation for speed control are described, using a simple linearized model for a powered-lift aircraft operating on the backside of the drag curve and at a fixed setting of propulsive lift. It is shown that an automatic speed-hold system incorporating heave-damping augmentation can allow use of the front-side control technique with satisfactory handling qualities, and the results of previous flight investigations in this connection are reviewed. The emphasis of this investigation, however, was on the manual control considerations, as they might be involved following failure of the automatic system. The influence of alternative cockpit controller configurations and flight-director display features were assessed for their effect on the control task, which consisted of a straight-in steep approach flown at constant speed in simulated instrument conditions.

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