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OUTER-LOOP CONTROL FACTORS FOR CARRIER AIRCRAFT

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Outer-loop control factors are those qualities that affect the pilot's ability to regulate manually glideslope, angle of attack, and lineup during the final approach. This report concentrates on the first two, glideslope and angle of attack. The objective is to identify the crucial attributes that ensure effective outer-loop control, then to examine how well existing design requirements address such attributes. A combination of flying qualities and performance requirements applies to this area, including MIL-F-8785C, MIL-STD-1797A, and the Navy's approach-speed criteria. First, the report reviews the topic in terms of historical background, discusses the technical approach, and previews the analytical tools to be applied. Second, it gives the status of outer-loop control, including a description of the carrier landing task, existing aircraft characteristics, and some data describing in-flight simulated carrier approaches. A description follows that contains math model components of the task, the aircraft, and the pilot. The main section of the report presents a series of analyses that are useful in pinpointing crucial outer-loop control features. The final section gives conclusions and recommendations for implementing results. The technical approach applies

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linear-systems analysis methods to low-order dynamics, mainly first- and second-order. The time domain is used to portray most results. The assumption of pitch-attitude constraints simplifies analysis by partitioning away higher-order dynamics of the flight control system and aircraft pitching-moment equations. This permits full appreciation of the role of aircraft lift, drag, and control or engine lag influences on outer-loop dynamics. Based on a system view of the pilot-vehicle-task combination, the relevant outer-loop control factors include: (i) Steady-state flightpath authority, (ii) short-term flightpath response, (iii) cue availability, (iv) safety margins, (v) commensurate amounts of pitch and thrust control, (vi) control quickness, (vii) established technique, and (viii) quality or shape of response. Current design requirements do not address effectively short-term flightpath response, control quickness, established technique, and quality of response. Analysis of the Navy popup maneuver shows it to be mainly dependent upon the margin from stall. One device for examining multiple aspects of outer-loop control is the “last significant glideslope correction.” It is an analytically-generated spatial envelope that bounds the maximum amplitude of a glideslope correction as a function of range from the ship. The method explores various outer-loop control factors and underlines the importance of short-term response and control quickness for glideslope control. Based on the analytical results, it is necessary to expand and better quantify currently-used design requirements to include those factors crucial to the carrier landing task. A combination of manned simulation and in-flight verification can do this best.

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LIST OF SYMBOLS

symbol	*definition*	*units*
AOA	angle of attack	units, deg
AOA_{com}	angle of attack command	units, deg
AR	wing aspect ratio, b^2/S	n/d
b	wing span	ft
b_{AOA}	AOA indicator bias	deg
c, cbar	wing mean aerodynamic chord (MAC)	ft
cg	center of gravity (fraction of MAC)	n/d
C_L	lift coefficient, Lift/S/q	n/d
$C_{L\alpha}$	lift curve slope, $\partial C_L/\partial \alpha$	1/rad
C_D	drag coefficient, Drag/S/q	n/d
C_{Do}	minimum-drag coefficient	n/d
C_{Di}	induced-drag coefficient	n/d
C_{DC_L}	$\partial C_D/\partial C_L$	n/d
$C_{D\alpha}$	$\partial C_D/\partial \alpha = C_{DC_L} \cdot C_{L\alpha}$	1/rad
d	glideslope error	ft
d_{com}	glideslope command	ft
$\dot{d}$	glideslope error rate	ft/sec
e	Oswald efficiency factor	n/d
f_o	effective frontal area, $C_{Do} \cdot S$	ft^2
g	gravity constant	ft/sec^2
h	altitude	ft
i_T	thrust incidence relative to FRL	deg or rad
K	system gain	
K_{AOA}	AOA indicator proportionality factor	units/deg
l	distance	ft
m	mass	slug
MAC	mean aerodynamic chord, c	ft

LIST OF SYMBOLS, Continued

symbol	*definition*	*units*
M_α	$1/I_y \cdot \partial M/\partial \alpha$	$1/sec^2$
$M_{\delta e}$	$1/I_y \cdot \partial M/\partial \delta e$	$1/sec^2$
n	load factor	g
$n_{x\alpha}$	$\partial n_x/\partial \alpha$	g/rad
$n_{z\alpha}$	$\partial n_z/\partial \alpha$	g/rad
N^{γ}_{θ}	flightpath angle numerator for attitude control	
$N^{\gamma}_{T/W}$	flightpath numerator for thrust control	
N^{α}_{θ}	angle-of-attack numerator for attitude control	
$N^{\alpha}_{T/W}$	angle-of-attack numerator for thrust control	
N^{u}_{θ}	airpseed numerator for attitude control	
$N^{u}_{T/W}$	airspeed numerator for thrust control	
q	dynamic pressure	$pound/ft^3$
s	Laplace operator	rad/sec
S	wing area	ft^2
t	time	sec
T	thrust	pound
T_1	effective first-order time constant used to lump airframe lag factors	sec
T_2	effective first-order time constant used to lump control lag factors	sec
TW	thrust-to-weight ratio, T/W	n/d
$T_{\theta 1}$	long-term factor in θ/δ_e numerator	sec
$T_{\theta 2}$	short-term factor in θ/δ_e numerator	sec
T_{h1}	long-term factor in γ/δ_e numerator	sec
T_{h2}, T_{h3}	short-term factors in γ/δ_e numerator	sec
$T_{h\theta}$	factor in $\gamma/\Delta TW$ numerator	sec
T_{u1}	short-term factor in u/δ_e numerator	sec
$T_{u\theta}$	short-term factor in $u/\Delta TW$ numerator	sec

LIST OF SYMBOLS, Continued

symbol	*definition*	*units*
u	velocity along x-axis	ft/sec
V	true airspeed	ft/sec, kt
V_C	closure speed	ft/sec, kt
V_S	stall speed	ft/sec, kt
V_{SPA}	stall speed for the power approach configuration (power on)	ft/sec, kt
w	velocity along z-axis	ft/sec
W	weight	pound
X_{TW}	$1/m \cdot \partial X/d\Delta TW$	
X_u	speed damping, $1/m \cdot \partial X/\partial u$	1/sec
X_w	$1/m \cdot \partial X/dw$	1/sec
X_α	$1/m \cdot \partial X/\partial\alpha$	ft/sec^2
y	lateral position	ft
Z_{TW}	$1/m \cdot \partial Z/d\Delta TW$	
Z_u	heave damping, $1/m \cdot \partial Z/\partial u$	1/sec
Z_w	$1/m \cdot \partial Z/dw$	1/sec
Z_α	$1/m \cdot \partial Z/\partial \alpha$	ft/sec^2
α	angle of attack	deg or rad
α_{com}	angle of attack command	deg or rad
β	angle of sideslip	deg or rad
γ	flightpath angle	deg or rad
δ	control surface deflection	deg or rad
δ_e	elevator or horizontal tail deflection	deg or rad
Δ	transfer function denominator	
Δd	incremental glideslope error	ft
$\Delta \dot{d}$	incremental glideslope error rate from trim	ft/sec
ΔTW	incremental thrust-to-weight ratio	n/d
Δu	incremental speed from trim	ft/sec
Δw	incremental z-velocity from trim	ft/sec
$\Delta \alpha$	incremental angle of attack from trim	deg or rad
$\Delta \gamma$	incremental flightpath angle from trim	deg or rad
$\Delta \varepsilon$	angular error from FLOLS glideslope	deg or rad

LIST OF SYMBOLS, Concluded

symbol	*definition*	*units*
$\Delta\theta$	incremental pitch attitude from trim	deg or rad
ζ	damping ratio	n/d
ε	angular error from FLOLS glideslope	deg or rad
η	thrust inclination relative to stability axis, $\alpha+i_T$	deg or rad
θ	pitch attitude	deg or rad
λ	lateral flightpath angle	deg or rad
λ_{GS}	glideslope correction scale length	ft
π	3.1415927...	deg or rad
ρ	air density	slug/ft^3
τ_o	pilot's effective delay	sec
φ	bank angle	deg or rad
ψ	heading angle	deg or rad
ω_{BW}	bandwidth	rad/sec
ω_n	natural frequency	rad/sec
ω_p	phugoid natural frequency	rad/sec
ω_{sp}	short period natural frequency	rad/sec

subscript	*definition*
BW	bandwidth
PA	power approach condition
TW	derivative with respect to thrust-to-weight
p	phugoid
s	stall
sp	short period
u	derivative with respect to u-velocity
w	derivative with respect to w-velocity
α	derivative with respect to angle of attack
θ	derivative with respect to pitch attitude
†	denotes a trimmed derivative

FOREWORD

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OUTER-LOOP CONTROL FACTORS FOR CARRIER AIRCRAFT

1. INTRODUCTION

This section gives the reader an introduction to outer-loop control factors. It begins with a statement of the purpose followed by a historical review. The section ends with a description of the technical approach and an introduction to the math modeling techniques used extensively in subsequent sections.

1.1 Purpose

Outer-loop control factors are those features that affect the ability to manage flightpath and speed during the final approach. The term *outer-loop* refers to the general manual-control loop structure in which path and speed are the outermost loops. The *inner-loop* controls consisting of pitch attitude, bank angle, and thrust support the outer loops. Outer-loop control factors will be extended to include *outer-loop flying qualities* as the ideas include some aspects of traditional flying qualities.

Effective management of flightpath (in both the vertical and horizontal planes) and angle of attack is crucial to the success of an arrested landing aboard a carrier. It is crucial in helping the aircraft to arrive at the terminal condition (engagement of the tailhook) or, alternatively, to make a safe waveoff or bolter. Further, the needed precision of the terminal condition over a short time makes this outer-loop control task especially demanding.

The subject of *outer-loop control* combines the traditional disciplines of both *stability and control* and *performance.* This is so partly because of how procuring agencies have set existing design requirements. There are also some aspects of outer-loop control that currently may not be covered by the specifications or the design requirements of either discipline.

The objective of this report is not only to describe the topic of outer-loop control, but to approach it in a way that exposes the effects of the physical features of the total pilot-vehicle-task (PVT) system. In doing so, the author has used simple classical control analysis techniques liberally. Also, descriptions and analyses of past and present aircraft designs help to illustrate various features.

Ultimately, the analysis presented in this report leads to an assessment of design requirements that affect outer-loop control, both directly and indirectly. Also it results in commentary on aspects not currently covered by such requirements and offers suggestions for other analyses or experimentations that may be useful.

1.2 Background

The carrier landing is a major design issue for Navy aircraft. Precise control of flight path and speed must be made within the narrow time and space bounds of the final approach leg. Simultaneously, the aircraft often requires high performance at other extremes of the envelope. While these design factors can force the use of complex displays and flight control systems (FCS), there are some basic airframe and engine attributes still needed. In general, these airframe and engine factors relate to outer-loop control. Moreover, they are not amenable to easy solution by clever FCS design because of the prevailing influence of basic lift, drag, and thrust characteristics.[1] Outer-loop control requires “muscle” because it deals with changes in flightpath and the accompanying applied forces to make them.

It is convenient to establish a simple scheme for defining the relationship among the pilot, the aircraft, and the total flight task when viewing outer-loop control. This can be effectively done using a feedback control system loop structure. Figure 1-1 diagrams such a structuring of manual control as applied to an aircraft.

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[1] This assumes that flight control systems are tied to basic control surfaces, i. e., they produce roll, pitch, and yaw moments only. Outer-loop characteristics can be altered if flight controls are extended to force-producing controls such as flaps, speedbrake, or engine thrust.

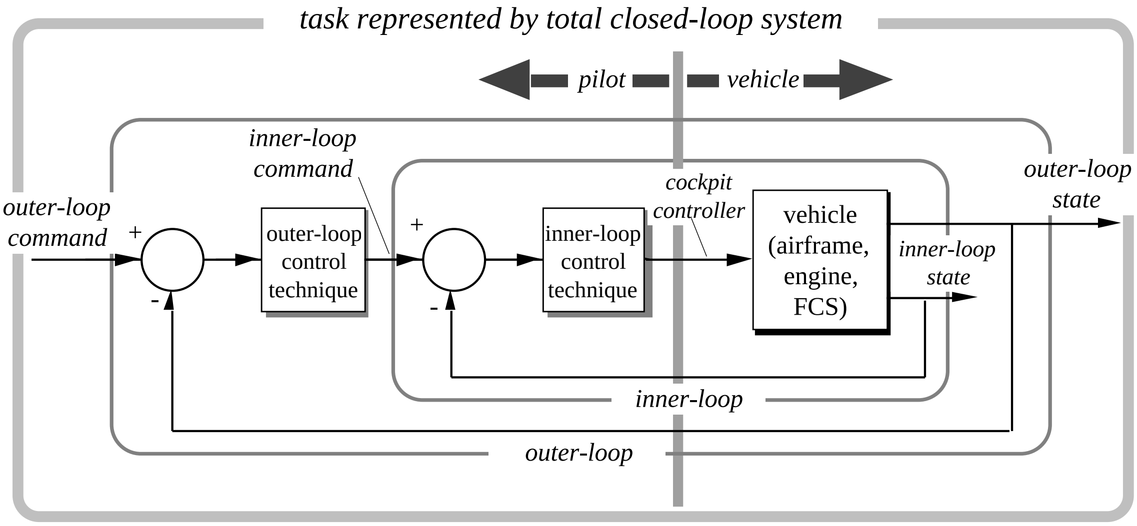

Figure 1-1. Scheme for Portraying the Pilot-Vehicle-Task System.

The benefits of this kind of scheme are that all the components—pilot, aircraft, and task—can be viewed in a common mathematical framework. The scheme induces the engineer to quantify some aspects not often viewed in strictly engineering terms, namely, those concerning the pilot and the task.

For the carrier landing task the outer-loop states are glideslope, angle of attack, and lineup. The inner-loop states are pitch attitude, thrust, and bank angle. Controls for the inner-loop states are the traditional set consisting of longitudinal-stick, lateral-stick and throttle. Controls for the outer-loop states can be equated to the inner-loop state commands (attitude command, thrust command, and bank angle command). This provides a neat "partitioning" of the pilot and aircraft and simplifies many aspects of the total task (carrier landing) system.

Just as a practical consideration, outer-loop flying qualities need to be partitioned from inner-loop features. This would permit the handling of aircraft with advanced FCS configurations without dealing with their complexity. The analysis techniques used here make this feasible, especially the use of pitch-constrained equations of motion to describe the aircraft and the inner-loop functions of the pilot.

Though the "outer-loop" control tasks of *glideslope, angle-of-attack,* and *lineup* are crucial, existing flying qualities specifications or design standards only partially address them. One important objective of this report is to examine in detail the factors that determine outer-loop flying qualities in order to set design requirements better.

1.2.1 Current Standards and Philosophies

There is not a clear structuring of inner- and outer-loop flying qualities characteristics for use in aircraft design. This is true both in MIL-F-8785C (Reference 1) and in the current MIL-STD 1797A specification for flying qualities of piloted airplanes (Reference 2). Sections that deal with inner-loop features, e. g., short-period dynamics, include some aspects of flightpath and speed control. The sections of MIL-STD 1797A that address explicitly outer-loop control contain only general background information and do not offer much specific guidance for carrier aircraft, especially concerning speed (or angle-of-attack) control.

MIL-STD 1797A correctly identifies $1/T_{\theta_2}$[2] as the primary influence in flightpath response, but establishes values only indirectly.[3] It does not give rationale for why $1/T_{\theta_2}$, a time response feature, should be scaled with $n_{z\alpha}$, an outer-loop control sensitivity factor. Nor does it say why 135 kt should be used as the scale factor. It will be seen that some current carrier aircraft have values considerable lower than this limit.

MIL-STD 1797A and MIL-F-8785C address speed control only in terms of *speed stability*. Neither document recognizes that Navy aircraft (nor most current military aircraft) do not use a speed reference, but angle of attack instead. While these specifications bound the short-period dominant mode seen in angle-of-attack (α) response to elevator, this mode is not particularly relevant to the outer-loop control situation. It especially does not relate to loose regulation of angle of attack.

Speed damping is one aspect of speed control that current design requirements do not address in any way. This parameter, $1/T_{\theta_1}$, can be characterized as the speed-damping counterpart to heave damping, $1/T_{\theta_2}$. One simulation experiment that focused on this feature showed a high sensitivity of pilot rating (Reference 3). It will be shown that

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[2] $1/T_{\theta_2}$ is a parameter frequently referred to in this report. It and others are defined in the glossary at the end of the report as well as in the body of the report itself.

[3] Minimum $1/T_{\theta_2}$ is computed based on a minimum $n_{z\alpha}$ and an airspeed of 135 kt.
$(\text{Min}\ (1/T_{\theta_2}) = \min(n_{z\alpha}) \cdot\ g/V = 2.5\ g/\text{rad} \cdot\ 32\text{ft/sec}^2 / 228\text{ft/sec} = 0.35\ \text{sec}^{-1})$

$1/T_{\theta_1}$ relates to the speed-stability factor found in current specifications, $\partial \gamma / \partial V$. Also $1/T_{\theta_1}$ may have more fundamental effects on successful manual control of flightpath and speed.

There is no requirement for an adequate level of flightpath control power or authority in either of the flying-qualities specifications. Although it may be more correctly viewed as a *performance* feature. Yet, the design requirements that most effectively address outer-loop control at this time fall under a *performance* classification, namely, the Navy V_{PA} criteria. These criteria cover several factors that shall be introduced shortly and later analyzed in depth.

No design requirement addresses explicitly outer-loop control factors for the lineup task, although one should not necessarily view this as an oversight. Kinematic relationships strongly constrain lineup control features (lateral flightpath response), at least for coordinated turns. So long as the existing flying qualities requirements adequately cover turn-coordination quality, there may not be a need for additional requirements. Unfortunately, those turn coordination requirements in both MIL-STD 1797A and MIL-F-8785C are difficult to interpret in direct physical terms[4]. They might be better stated with respect to the relationship between turn initiation (bank angle) and resulting lateral flightpath (heading response or y-velocity response). But this will not be discussed further in this report.

Because of limits imposed by the contract covering this study, the subject of outer-loop control in the horizontal-plane is not be addressed here other than to define its role in the total carrier landing task. Also, for the longitudinal axes, there is no consideration of the use of auxiliary flightpath and speed controls such as direct lift control or speedbrake modulation. Although, there will be some general conclusions drawn based on the analyses that can be applied to these other controls.

1.2.2 Navy Approach Speed Criteria

The current criteria that define the approach speed, V_{PA}, combine to set several flying qualities and performance characteristics for Navy carrier aircraft (such as are given in References 4 and 5). The Navy approach speed criteria are closest to an explicit outer-

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[4] Specifically, the roll rate oscillation limitations, bank angle oscillation limitations, and sideslip excursion limitations as given in Section 3.3.2 of MIL-F-8785C.

loop control requirement for carrier aircraft. These criteria address not only stability and control and performance, but also flying qualities, visibility, safety margins, and engine response. Therefore they are worthy of scrutiny in this study.

The Navy V_{PA} criteria combine in a synergistic way and appear to have worked effectively for nearly 30 years. But, the variety of effects are sufficiently complex and interactive to impede a clear understanding by engineers and pilots alike.

One purpose of this report is to present background for Navy approach speed criteria and to analyze their effects on aircraft design, flying qualities, and performance. The author presents a brief historical sketch followed by a discussion of each component of the criteria in basic engineering terms. This prepares the way for development of an audit trail between airplane design features and mission performance consequences for carrier aircraft. The analysis of approach speed criteria is finally tied to actual Navy aircraft so that maximum use can be made of historical data.

Historical Sketch

The Navy approach speed criteria consist of several parts, the most notable of which is the "popup" maneuver. The popup is a large-amplitude pitchup aimed at gaining a given height change within a specified time. Other conditions support the popup, including visibility, safety, and the ability to sustain the altitude gain through use of the engine.

Most of the Navy approach speed criteria stem from a 1953 McDonnell Aircraft Corporation report based on flight experience with both the USAF XF-88A and Navy XF3H-1 fighter aircraft (Reference 6). It was found that pilots needed to use higher approach speeds than those previously based on 1.1 V_S.[5] This report proposed a set of rational criteria to account for (i) speed loss due to potential energy increase, (ii) induced drag, and (iii) thrust variation. It defined an analytical speed prediction method in terms of a fixed-throttle pitch up maneuver nearly identical with the current popup maneuver.

During the next few years the Navy, NACA, RAE, and the airframe contractors collected operational and experimental data (References 7 through 15). Determination of minimum acceptable approach speed was the objective of several research and flight test

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[5] Stall speed with approach power setting.

activities.

In 1959 Mr. Jack Linden drafted a BuAer memo (Reference 16) discussing the need for the Navy to consider a more realistic minimum speed criteria than simply 1.3 V_S.[6] He recommended the McDonnell method described in the Shields report and cited flight test experience from NASA Ames Research Center (Reference 10). Any method of approach speed selection needed to consider a multitude of features, including altitude control, visibility, stall proximity, stability and control, engine response, and use of speedbrake. The 1961 VAX Request for Proposals, the design competition resulting in the A-7 airplane, implemented recommendations from the Linden memo.

Beginning in 1964, NATC began a series of flight test evaluations applying the "step-up" or "popup" maneuver to several fleet aircraft. These included the F-4B, F-8C[7], A-4E, RA-5C, and A-3B.[8] These actions developed test methods evolved rules defining maneuver performance. There were some notable interpretations of how the magnitude of the pitch-up should b[9]e set and what should occur following the required altitude change. References 17 through 22 reported this series of flight tests. NATC subsequently tested the A-7, the first aircraft designed with these criteria (Reference 23). Several memoranda and papers concerning this testing documented and discussed the criteria then being developed, applied, and refined (References 24 through 28).

The minimum approach speed issue became especially crucial around 1967 with two aircraft, both having fan engines and the accompanying long lag in thrust response. One of these aircraft was the F-111B, a large and heavy carrier-based design with a guaranteed minimum approach speed of 113 kt at its maximum landing gross weight of 56,000 lb. The other aircraft design with interesting properties was the Royal Navy F-4K, a Phantom airframe using Rolls Royce Spey engines instead of the original J79 conventional turbojet engines (References 29 and 30). Neither design survived as a carrier-based aircraft, and the respective minimum approach speed issues of each passed from the scene.

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[6] The current minimum speed criterion at that time, January 1959.

[7] With and without DLC.

[8] Standard wing version of the A-3 (i. e., without the cambered leading edge modification).

[9] One major issue was whether the peak angle of attack change was based on the maximum Δ g based on the static margin from C_{Lmax} or on the "available" margin which could be obtained in an actual pitchup maneuver. The former became the rule.

The Navy maintained the V_{PA} criteria through the 70's and 80's with designs that were generally not lacking good carrier approach flying qualities. These included the F-14, S-3, and F/A-18 (Reference 31).

Summary of Approach Speed Criteria

The design criteria that most directly affect outer-loop flying qualities are summarized below. (Section 4 states them fully and gives a detailed analysis.) In general, the approach speed must be fast enough to meet all the following minimum conditions:

(i) *Longitudinal acceleration (waveoff):* Level-flight acceleration of 5 ft/sec^2 within 2.5 seconds.[10]

(ii) *Stall margin:* Approach speed greater than 1.1 V_{SPA} (power on).

(iii) *Visibility over the nose:* pilot can see stern waterline when intercepting 4° GS at 600 ft altitude.

(iv) *Handling qualities:* Can satisfy MIL-F-8785C stability and control requirements.

(v) *Time to make glidepath correction (popup maneuver):* Using pitch attitude only, transition to a new glidepath 50 ft higher in 5 sec without exceeding half the available load factor.

(vi) *Engine acceleration:* For a step throttle commands equivalent to ± 3.86 ft/sec^2, achieve 90% of the acceleration in 1.2 sec.

There have been several variations on the above requirements over their existence, beginning about 1960. For example, the popup maneuver once consisted of a 50 ft altitude change starting and ending in level flight. Another variation allowed 7 seconds but required a recapture of the glideslope within that time.[11] Also, the available load

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[10] Military thrust and speedbrake retraction are generally assumed.

[11] This procedure introduced a pilot-in-the-loop aspect to the criterion, something which unfortunately is often viewed as being too subjective. The Navy eventually returned to the

factor has been also interpreted as that obtainable in a dynamic maneuver rather than based on the static lift coefficient. The current requirements evolved, in part, to accommodate flight test procedures.

1.3 Technical Approach to Examining Outer-Loop Control Factors

The technical approach to examining outer-loop control factors that is to be used here consists of: (i) Examine existing aircraft with respect to the carrier landing task. (ii) Model and analyze the components of the pilot-task-aircraft system. (iii) Itemize the outer-loop control factors that are actually covered. And, (iv) recommend steps to fill gaps in existing requirements. These steps are carried out with the aid of an analytical tool that simplifies and emphasizes the outer-loop control aspects, namely the use of constrained-pitch-attitude dynamics. This tool will be introduced in the following subsection.

First, a comprehensive description of the carrier landing task serves as the basis for the analysis that will follow. There are several perspectives for viewing the task. These include the sequence of events leading to the final approach leg, the parameters that define performance of the final approach and landing task, and guidance information that the pilot uses.

It is also instructive to have a view of various existing Navy carrier aircraft in terms of their outer-loop flying control parameters in the PA (Power Approach) configuration. A survey of several current and past aircraft designs provides a frame of reference.

Each part of the pilot-task-aircraft system is then analytically examined. To the greatest extent possible, this is done using consistent mathematical terms across the total closed-loop system. As a rule, linear ordinary differential equations model the total system except for “limiter” nonlinearities[12] on some control and display elements. Yet,

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more “open-loop” five-second popup criterion. Later this report will describe how the open-loop popup maneuver omits an important ingredient in the array of desirable outer-loop control factors.

[12] A *limiter* in a control system context is simply the maximum authority achievable in terms either of the amount of the input (control) available or of the output (state-variable response) that can be obtained.

these nonlinearities do not invalidate the linear analysis technique.

Next the math model is analyzed to expose the primary features. The author distinguishes between those features mainly related to the physical aircraft design and those that describe the outer-loop state variable response. This is simply the difference in an *engineer-centered* point of view and a *pilot-centered* one.

Conclusions are summarized in terms of (i) outer-loop control factors and (ii) implications for some supporting inner-loop characteristics. Recommendations for experimental verification of the analysis results follow these conclusions.

Combined Pilot-Vehicle-Task System

As a first step to constructing an audit trail of outer-loop control factors, one must consider the combined PVT system. Several studies have analyzed the pilot-in-the-loop, References 32 through 37, for example. These studies have progressed from an emphasis on inner-loop aspects to one on mainly the outer-loop. This report draws upon these earlier approaches but tries to minimize the analytical complexity.

Figure 1-2 shows the set of components that described the total vehicle system dynamics in the carrier landing task. This includes the elements which represent inner-loop control, outer-loop control, and displays.

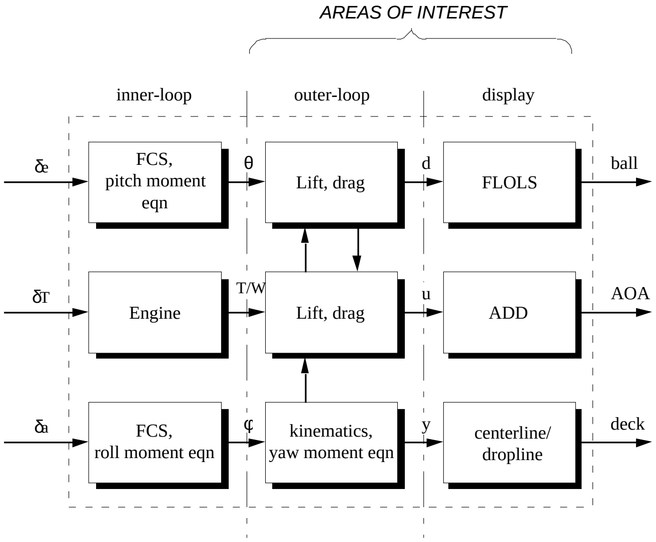


Figure 1-2. Topology of Carrier Landing Aircraft System

Some blocks in the above diagram will be described in explicit analytical terms in the short introductory technical overview of the next subsection, namely the aircraft-related outer-loop components (aerodynamic lift and drag).

1.4 Introductory Technical Overview

The following is a brief overview of several fundamental ideas and physical relationships. It is an initial application of the technical approach that illustrates how the PVT system can be modeled with each component in consistent mathematical terms. The purpose is to present a simple statement of concepts that will be developed later in more detail. A natural progression follows from (i) the task considerations, (ii) the implied relevant dynamic response features, and (iii) the contributing physical characteristics.

1.4.1 Implications of the CV Approach Task

The task of the pilot in a manual CV approach is to arrive at the deck at the desired point, aircraft attitude, and speed. To do this, the pilot must follow a path prescribed by the FLOLS glideslope at a speed indicated by the α display. The correct attitude is a natural result of good stabilization on flightpath and speed. The pilot performs the task starting at the roll-out onto final about 3/4 nm behind the ship (about 25 seconds before touchdown).

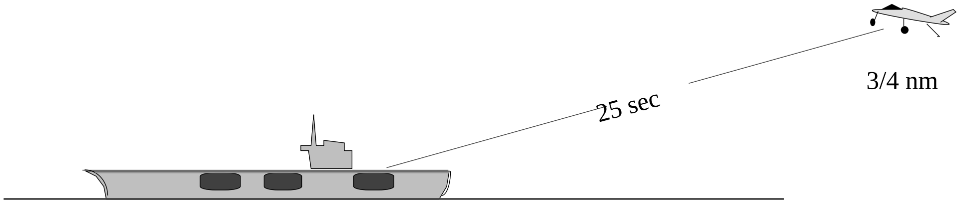


Figure 1-3. Range of Interest for CV Approach Task.

Therefore, this is a space- or time-bounded task with two primary controlled variables. Flightpath error is proportional to the angular error indicated by one of five discrete Fresnel lens cells referenced to a row of datum lights. The pilot sees speed error in terms of a head-up display of angle of attack relative to an on-speed reference.

1.4.2 Dominant Features of Aircraft Response

Equations of Motion

Given the above task considerations, the aircraft response can be viewed in simple terms of two states and two controls. The relevant states are flightpath angle, $\Delta\gamma$, and angle of attack, $\Delta\alpha$; and the controls are attitude, $\Delta\theta$, and thrust-to-weight ratio, $\Delta T/W$. In order to avoid several complications involving range dependence and quantization nonlinearities, $\Delta\gamma$ and $\Delta\gamma$ are selected in favor of the more explicit quantities of FLOLS meatball error and indicated α error.

The math model used to describe the aircraft and FCS can typically vary greatly in form and degree of complexity.

The basic equations of motion consist of "trimmed" x-force and z-forces:

$$a_x = \Delta\dot{u} = \Sigma X/m = X_u\,\Delta u + X_w\,\Delta w + g\,\Delta T/W \qquad (1)$$

$$a_z = -V\,\Delta\dot{\gamma} = \Sigma Z/m = Z_u\,\Delta u + Z_w\,\Delta w - \eta g\,\Delta T/W \qquad (2)$$

and the auxiliary relationships:

$$\Delta w/V = \Delta\alpha = \Delta\theta - \Delta\gamma \qquad (3)$$

or, combining these relationships in matrix form:

$$\begin{bmatrix} (s - Z_w) & Z_u \\ X_w & (s - X_u) \end{bmatrix} \begin{bmatrix} V\,\Delta\gamma \\ \Delta u \end{bmatrix} = \begin{bmatrix} -Z\alpha & \eta g \\ X\alpha - g & g \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta T/W \end{bmatrix} \qquad (4)$$

The determinant of the left side (characteristic) matrix, Δ,[13] is:

$$\Delta = (s - Z_w)(s - X_u) - X_w Z_u \approx (s + 1/T_{\theta_1})(s + 1/T_{\theta_2})^{14} \qquad (5)$$

---

[13] The symbol Δ is used both for the determinant of the characteristic equation (the denominator of any transfer function) as well as to denote an incremental state variable or control variable such as $\Delta\alpha$ or $\Delta\theta$. The distinction should be self explanatory in all cases.

[14] The factors appearing here follow the conventions described in Reference 38 and used widely by the aircraft flying qualities community.

Key numerators are similarly obtained and consist of:

$$N^{\gamma}_{\theta} = -Z_w \left[s - X_u + Z_u (X_\alpha - g) / Z_\alpha\right] = g/V \cdot n_{z\alpha} (s + 1/T_{h1}) \qquad (6)$$

$$N^{\gamma}_{T/W} = g/V (-Z_u - X_u \eta + \eta s) = 2 (g/V)^2 \cdot (1 + T_{h\theta} s) \qquad (7)$$

$$N^{\alpha}_{\theta} = \Delta - N^{\gamma}_{\theta} = s^2 - X_u s - Z_u g/V \qquad (8)$$

$$N^{\alpha}_{T/W} = - N^{\gamma}_{T/W} \qquad (9)$$

where $\Delta\gamma/\Delta\theta(s) = N^{\gamma}_{\theta}(s) / \Delta(s)$, or $\Delta\alpha/\Delta T/W(s) = N^{\alpha}_{T/W}(s) / \Delta(s)$, etc.; for example,

$$\frac{\gamma(s)}{\theta(s)} = \frac{-Z_w (s + 1/T_{h1})}{(s + 1/T_{\theta 1})(s + 1/T_{\theta 2})} \approx \frac{(s + \overset{\approx 0}{\cancel{1/T_{h1}}})}{\underbrace{(s + 1/T_{\theta 1})}_{washout} \underbrace{(T_{\theta 2} s + 1)}_{lag}} \qquad (10)$$

Reference 38 contains a comprehensive general treatment of the equations of motion and transfer functions for aircraft and flight control systems. However, the reader of this report will find that the above equations are uncomplicated and suffice for the purposes of the analysis performed here.

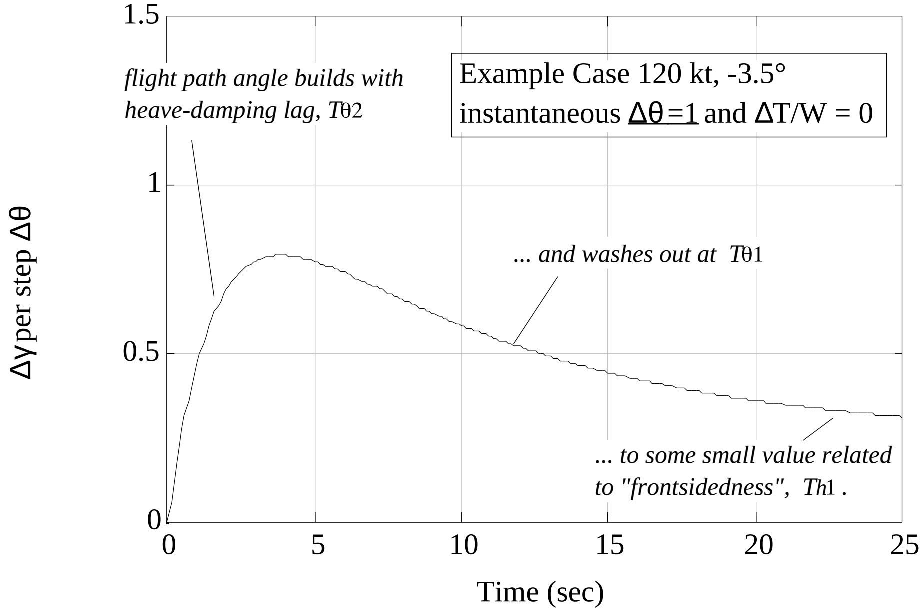
Response Shapes

The following plots show two sets of flightpath and α responses, one set for a pitch-attitude step and the second for a thrust step.

Consider first the response of flightpath angle and angle of attack to an instantaneous step pitch attitude change. Figure 1-4 shows that $\Delta\gamma$ follows $\Delta\theta$ with a short-term lag, $T_{\theta 2}$, then washes out with a slower time constant, $T_{\theta 1}$. The short-term amplitude approaches unity and the long-term amplitude is nearly zero, but depends upon the numerator factor $1/T_{h1}$.

The angle of attack response is simply the mirror image of flightpath angle since $\Delta\alpha = \Delta\theta - \Delta\gamma$. Angle of attack responds first with attitude, decays with $T_{\theta 2}$ and finally increases again more slowly with $T_{\theta 1}$.

a. Flight Path Response—Attitude Primary



b. Angle of Attack Response—Attitude Primary

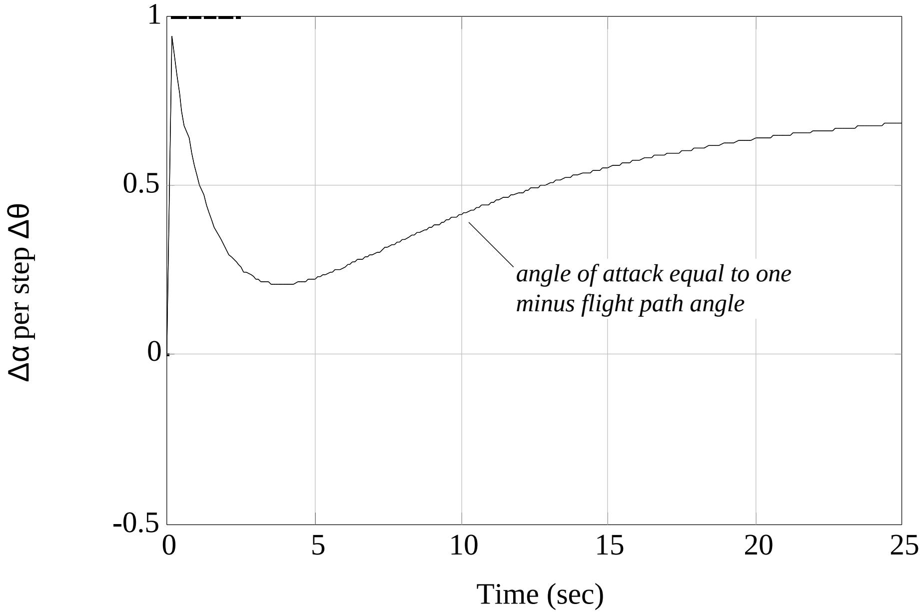
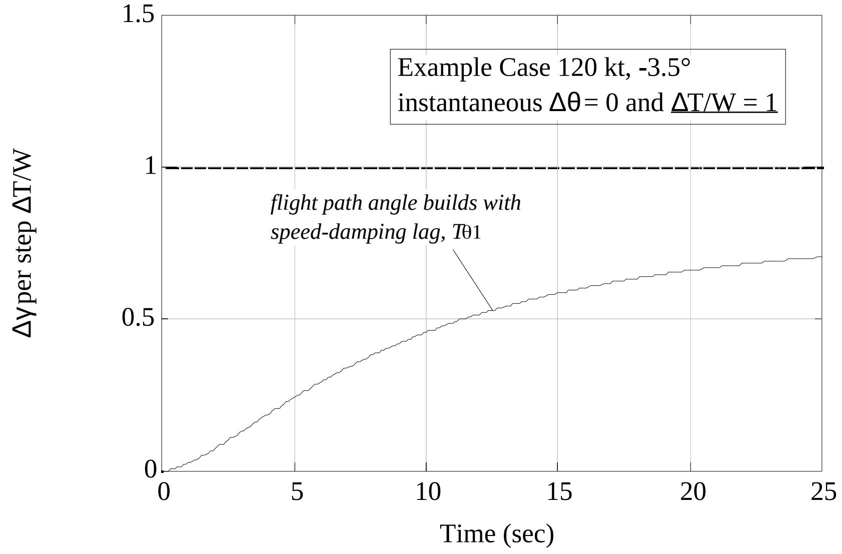


Figure 1-4. Flightpath and Airspeed Response to Attitude Change.

Next consider the use of thrust (normalized with aircraft weight), Δ T/W, and note the very different response shapes. Flightpath slowly increases without washout while α correspondingly decreases.

a. Flightpath Response—Thrust Primary



b. Angle of Attack Response—Thrust Primary

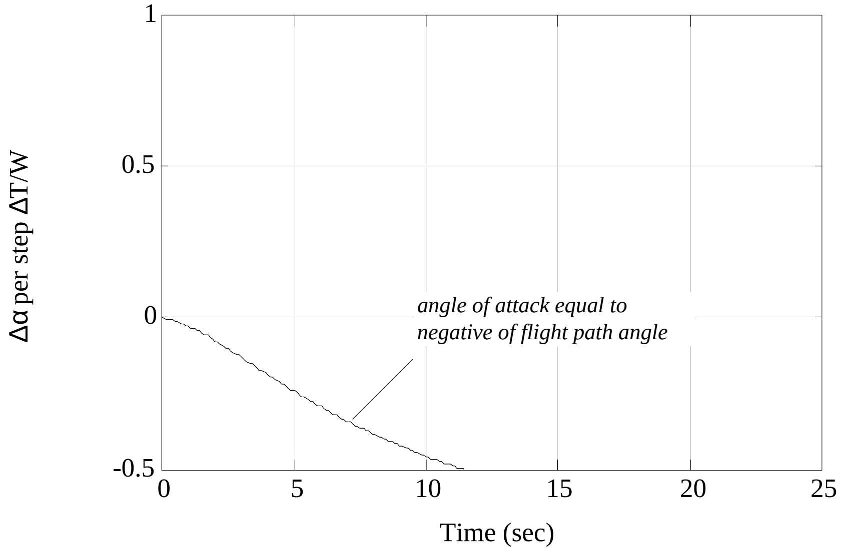


Figure 1-5. Flightpath and Airspeed Response Due to Thrust Change.

1.4.3 Aircraft Design Features

The physical factors that determine the above response relationships are few and confined to *mass*, *thrust angle*, and *aerodynamic lift and drag*. The lift and drag information necessary for the analysis performed in this report consists only of trimmed values as typified by the kinds of plots in Figure 1-6.

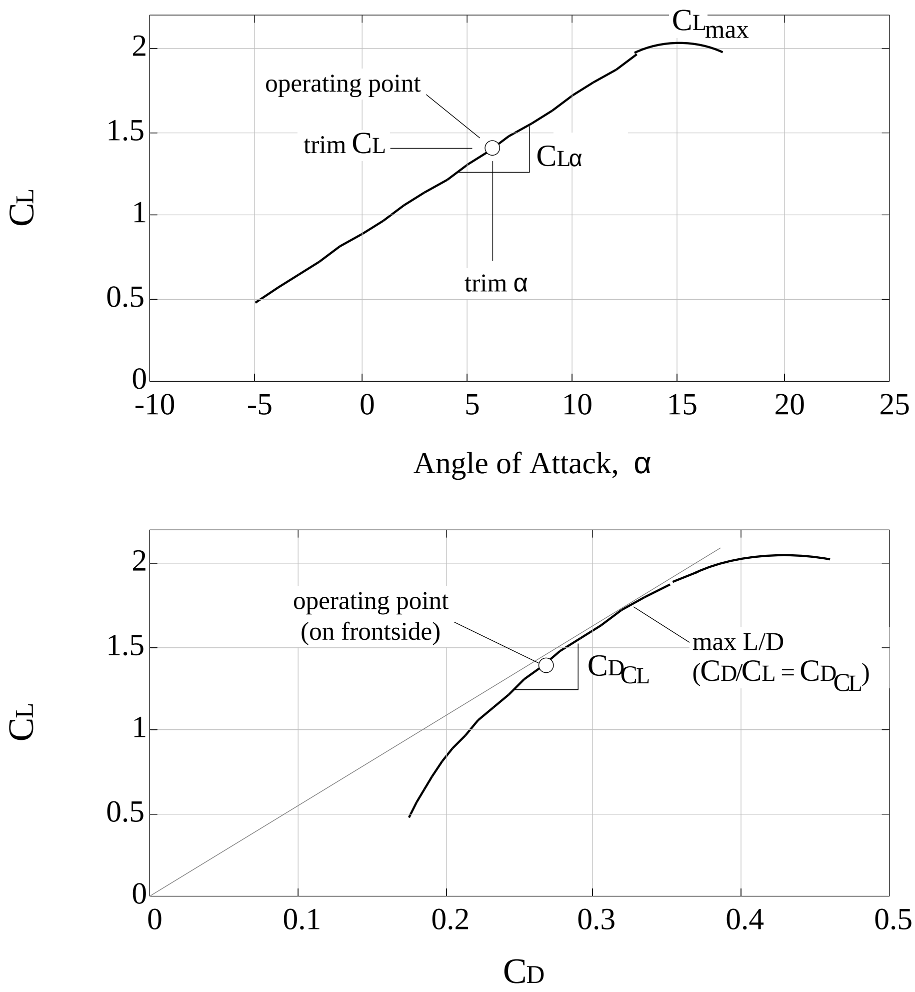


Figure 1-6. Summary of Key Aerodynamic Data.

The aerodynamic parameters that must be extracted from these plots include, C_L, C_D, $C_{L\alpha}$, and $\partial C_D / \partial C_L$ at the operating point as determined from flight condition. These, in turn, yield the following quantities representing aspects of the outer-loop response:

$$X_u = -\rho V S C_D / m = -2g / V \cdot C_D / C_L \tag{11}$$

$$X_w = \rho S V (C_L - C_{D\alpha}) / 2m = g / V \cdot (1 - C_{D\alpha} / C_L) = g/V \cdot (1 - n_{x\alpha}) \tag{12}$$

$$Z_u = -\rho V S C_L / m = -2g/V \tag{13}$$

$$Z_w^{\dagger} = -\rho V S \, (C_{L\alpha} + C_D) \; / \; 2m \quad \text{(where } Z_w^{\dagger}, Z_\alpha^{\dagger}, n_{z\alpha} \text{ are based on trim } C_{L\alpha}\text{)} \tag{14}$$

$$Z_{TW} = -\eta \, g \tag{15}$$

$$X_{TW} = g \tag{16}$$

$$n_{z\alpha} = (C_{L\alpha} + C_D) / C_L \approx C_{L\alpha} / C_L \tag{17}$$

$$1/T_{\theta 2} = g/V \, (n_{z\alpha}^2 - 1) / n_{z\alpha} \approx g/V \, n_{z\alpha} \tag{18}$$

$$1/T_{\theta 1} = g/V \cdot 2/n_{z\alpha} + 1/T_{h1} = g/V \cdot 2/n_{z\alpha} - g \cdot \partial\gamma / \partial V \tag{19}$$

This list will be presented in a more complete form in Section 3.

The math model thus derived is suitable for describing the flightpath and α response while neatly sidestepping the matter of inner-loop response. Such features as the short-period or control surface motions simply do not intrude.

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2. THE CARRIER LANDING TASK AND EXISTING AIRCRAFT

The following is a description of both the carrier landing task and various aircraft designed to perform it. The math models and analyses in subsequent sections make use of this information. Thus the main purpose of this section is to provide background information and a suitable context for the construction and use of mathematical models.

2.1 Carrier Landing Task Description

Navy pilots view the carrier landing as the most demanding of manual flight tasks for military aircraft. It must be performed under a wide range of visibility, weather, and sea-state conditions. Further, the pilot may be under substantial stress following combat or flight over an extended duration. If the carrier landing is part of a training mission, the pilot is likely to have only limited skill and experience.

There are several variations of the carrier landing task, including daytime VFR, nighttime VFR, and IFR. Pilots consider the nighttime carrier landing the most demanding. For its purposes, this study addresses the daytime VFR landing. This involves use of a *racetrack* pattern beginning with an upwind leg flown over the ship and ending with the final approach leg and arrestment. Further, this study focuses on the final approach leg. Important features are that the turn-to-final and touchdown spatially bound the task and the pilot is limited to visual guidance information from the deck.

Several sources serve as the basis for the task description, including interviews with Navy carrier pilots, LSO literature, carrier-qualification training manuals, and several related carrier landing systems descriptions (References 39 through 46).[15]

2.1.1 General

Four main segments comprise the VFR carrier landing pattern as Figure 2-1 shows (Reference 39). These segments consist of (i) the downwind leg overhead the carrier, (ii) the “break” maneuver and downwind leg, (iii) the turn to final, and (iv) the final approach leg. Each segment involves its own set of guidance information, pilot control technique, and aircraft flight condition and configuration.[16]

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[15] The main source of information was a series of interviews with several active F-14 pilots at NAS Miramar during 1982 and 1983.

[16] This breakdown was made in Reference 29 on the basis of distinguishing where there were significant

The general success of the approach depends upon each segment ending with correct position and flight condition parameters. Since the geometry constrains the approach task, there is little slack time for the pilot to recover from any large off-nominal condition. Therefore the objective is always to stay a bit ahead of each milestone.

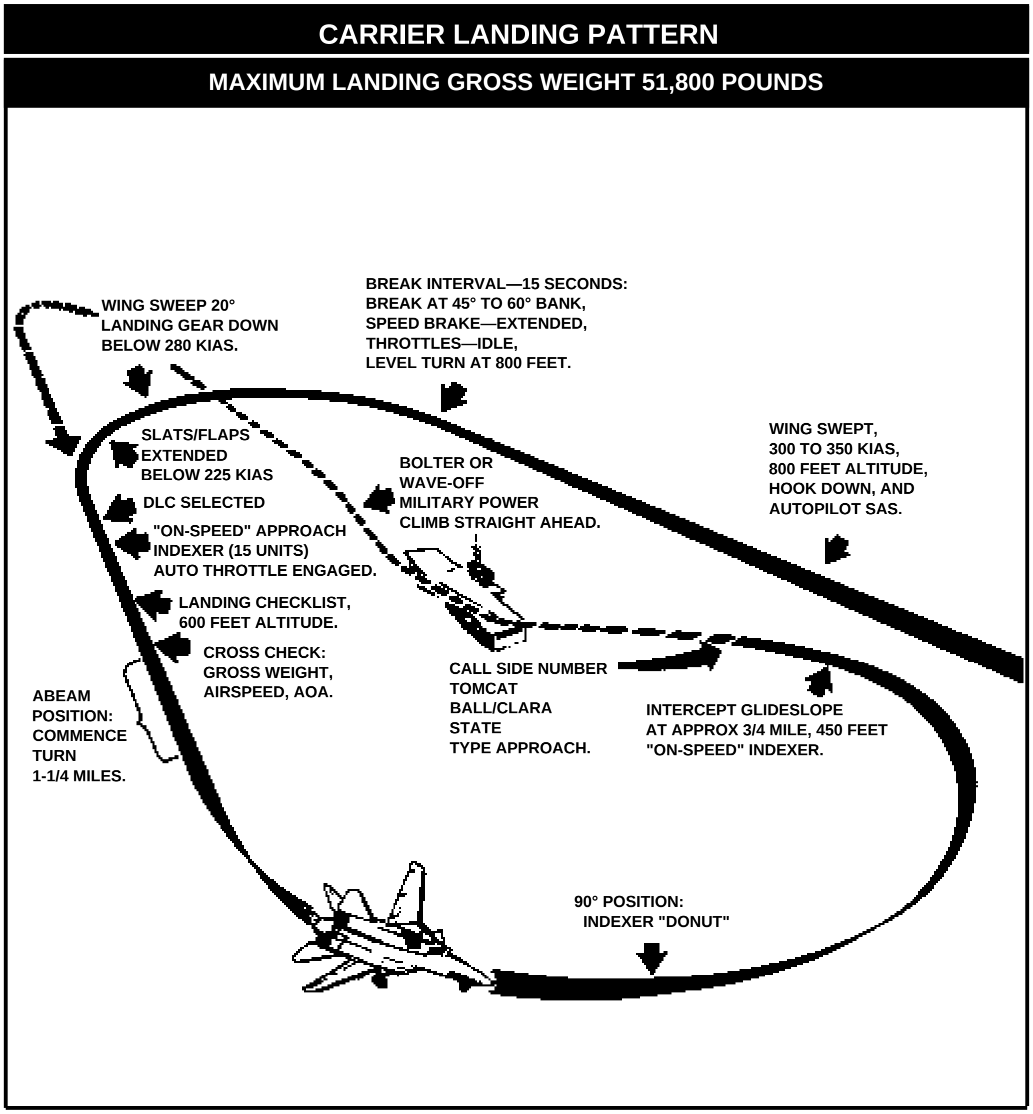

Figure 2-1. Carrier Landing Pattern as Described in NATOPS.

shifts in the basic pilot control strategy.

Initial Leg

The pilot flies the initial leg to arrive overhead the carrier on a standard course, heading, and altitude in preparation for executing the racetrack pattern. This leg begins nominally three miles astern the ship at 1200 ft and ends over or slightly beyond the bow. For the lead aircraft the main task during the initial leg are to arrive over the bow, on the Base Recover Course (BRC), and at 800 ft altitude. Maintaining formation is the main task of aircraft flying formation on the lead aircraft. The lead aircraft sets the airspeed at 300 to 400 kt.

The pilot control strategy involves compensatory management of course and altitude using pitch and roll attitude, supported by vertical velocity and heading, respectively. With thrust set at a nominal fuel flow, the pilot does not regulate airspeed tightly.

Aircraft dynamics during the initial leg are benign and typically “frontside.” The high speed ensures small effective lags in pitch, roll, and flight path. The resulting mental effort required is therefore low. However, the large excess control capacity can be absorbed by decisional tasks connected with deck spotting and planning for a minimum-interval approach.

Break Maneuver and Downwind Leg

The break starts the 360° racetrack course and includes crucial deceleration and reconfiguration events. The segment ends with the pilot flying the downwind leg at a constant course and altitude. The objective of the break is to arrive at the turn-to-final (the next segment) in the landing configuration (PA) and trimmed for level flight at the approach α.

Initially the pilot flies the break segment as a largely *precognitive*, high-g, level-turn maneuver intended to reduce airspeed rapidly. The angle of bank during the break can be between 45° and 70° , depending upon the initial airspeed and the pilot's judgment of the resulting turn radius. No visual position cues relative to the ship are available until well around the 180° turn. At this point a minor heading change can be used to adjust the lateral distance from the ship.

The aircraft reconfiguration sequence effectively manages airspeed. The pilot deploys the speedbrake upon initiating the break. For the F-14, the pilot may leave the wings unswept, but only to realize the induced-drag benefit. As quickly as airframe limits permit, the pilot lowers the landing gear and extends the flaps.

The interval is about 30 sec from initiation of the break until the roll-out to wings-level on the downwind leg. The pilot then has another 15 to 20 sec to reach a well-stabilized flight condition and complete required check list procedures.

Turn-to-Final

The turn-to-final begins when the pilot is abeam the LSO platform at an altitude of 600 ft. Precisely at that point the pilot commands a constant-attitude bank angle to intercept the final approach leg down the deck centerline. For the F-14 a 27° bank is used.

The pilot targets an altitude of 450 ft at the 90° point in the turn, thus applying a loose regulation of vertical flightpath. Lateral path control during the turn is largely open-loop until the pilot begins to get lineup cues from the deck centerline.

At 45° from the BRC the Fresnel lens system begins to be visible thus permitting some vertical flightpath regulation. At nearly the same time, lateral path information based on deck geometry may induce some adjustment of bank angle.

Because pilot trims to the approach condition during the turn, flying qualities are typically “low-speed” with heave damping low, speed damping high, and adverse yaw a possible factor. For an aircraft such as the F-14, loss of lift due to lateral spoiler use can be a problem. Therefore the pilot may use lateral control sparingly to avoid upsetting sink rate.

As in the previous leg, geometry spatially bounds the turn-to-final task. The total period of the segment is about 30 sec at which point the pilot must begin intensive closed-loop control of glideslope, lineup, and angle-of-attack. If the turn-to-final ends on-speed and with correct height and lineup position, it minimizes the difficulty of the final leg.

Final Approach Leg

The final approach leg begins as the pilot rolls out on the deck centerline and begins precise tracking of the vertical flightpath. The position of the FLOLS “meatball” relative to the lighted datum bar gives vertical guidance information. The FLOLS assembly is positioned on the left edge of the deck about 500 ft ahead of the ramp. The pilot gets precise lateral path information using the deck centerline angle relative either to the horizon or to the vertical dropline at the stern. The latter is available even if the actual horizon is obscured or if operating at night.[17]

This is the most crucial approach segment because it ends on the deck. Successful recovery depends upon the hook passing high enough to clear the ramp and low enough to engage the furthest cross-deck pendant (#4 wire). However, the Landing Signal Officer (LSO) will insist on much tighter bounds.

From the time of roll-out to wings-level, the pilot has about 25 sec before reaching the deck. This period permits a limited number of corrections in Glideslope (GS), Lineup (LU), and angle-of-attack (AOA) such that all will be within acceptable bounds at the deck. In addition, the pilot must null all velocity and attitude states the end. Thus the final approach leg is a classical *terminal control* problem and is distinct from a *continuous tracking* control problem. Nevertheless, it is possible to employ some continuous-tracking analysis tools if the analyst adequately recognizes the role of the terminal constraints.

The pilot's success in managing the outer-loop states (GS, LU, and AOA) depends upon each having a suitably short time-to-achieve. In general this can be lumped into some effective first-order lag time constant. The respective control power is each case is implicit in the effective lag time.

The pilot's strategy for controlling outer-loop states becomes crucial to the final approach in that aggressive closed-loop activity is required (in contrast to the more open-loop nature in the other segments). The combination of long response lags and limited time-available requires that the pilot try to optimize use of controls.

The LSO has a major role in helping the pilot to maintain the final approach leg parameters should they begin to exceed prescribed LSO standards. The LSO has direct voice contact with the pilot and communicates using a standard vocabulary of about 50 phrases having several degrees of urgency. The calls are classified as “informative,” “precautionary,” and “imperative.” Besides voice calls, the LSO ultimately can command a waveoff through light signals presented on the FLOLS assembly.

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[17] Final approach guidance information is described in detail in Section 3.

2.1.2 Details of Task Performance

Performance nomenclature and standards used by the LSO community are useful in quantifying the performance of the carrier approach task. While defined in terms of the LSO's viewing position, they also have a strong correspondence to the pilot's view of the task. Also importantly, the LSO performance standards can be translated into engineering terms.

Figure 2-2 shows the terminology for describing the aircraft range-to-go on the final approach. The standard codes used are:

"X" start of approach (as the aircraft rolls out from the turn to final)
"IM" in-the-middle
"IC" in-close
"AR" at-the-ramp

The distances shown are approximate and sometimes divided into finer divisions.[18]

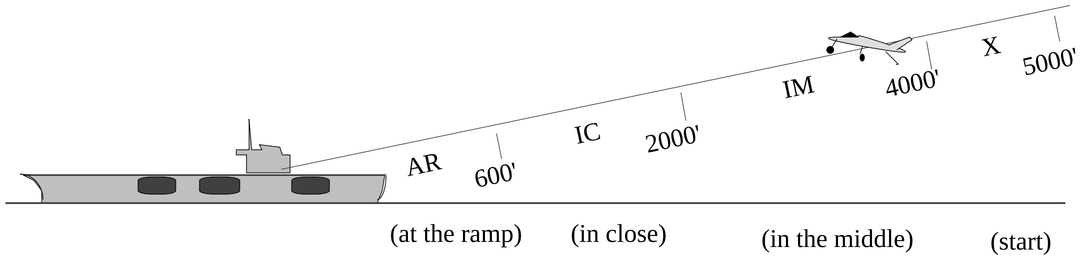

Figure 2-2. LSO Range Descriptors.

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[18] Some nominal distances for each segment are X 3/4nm, IM 1/2nm, IC 1/4nm, and AR 600 ft (nominally 100' aft of the ramp).

LSO nomenclature define vertical flightpath position in terms of the angular deviation from the nominal glideslope which usually ranges from 3.5° to 4° . Position on glideslope includes degrees of high [HI] and low [LO] deviations about the glideslope centerline [OK] as Figure 2-3 shows. "A little high" is signified by (HI), "moderately high" by HI, and "very high" by HI. A similar scheme is applied to the other kinds of deviations as shown below.

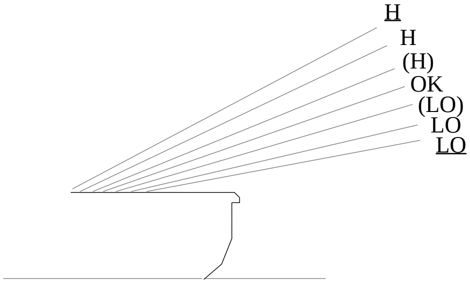

Figure 2-3. LSO Glideslope Descriptors.

LSO's specify angle of attack in terms of the equivalent airspeed deviation. High angle of attack is considered to be slow (SLO), low angle of attack is fast (F), and on-speed is (OK). Gradations of fast and slow are illustrated in Figure 2-4.[19]

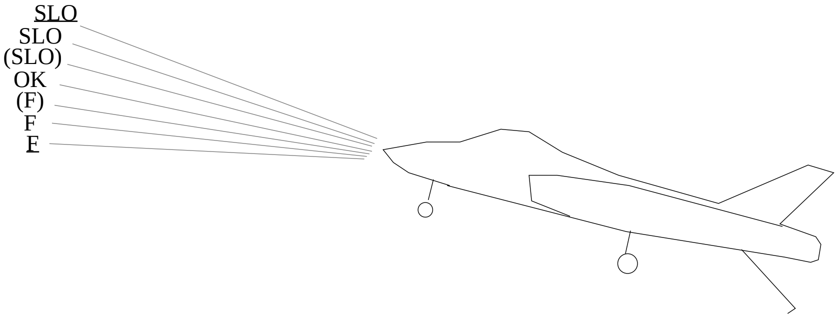

Figure 2-4. LSO Angle of Attack (Airspeed) Descriptors.

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[19] Numerical definitions of angle-of-attack status is generally specified for each aircraft in its respective NATOPS Manual.

Lateral flightpath position status consists of being lined up left (LUL) or lined up right (LUR) with respect to the canted deck centerline. Figure 2-5 shows the LSO gradations in lineup position.

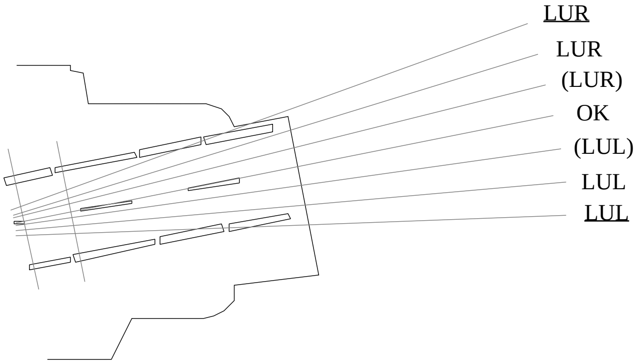

Figure 2-5. LSO Lineup Descriptors.

A set of specific values for the above descriptors is given in Table 2-1 based on the study of LSO procedures reported in Reference 45. In addition to the position states, rate-of-change states are also listed, i. e., sink rate and drift rate.[20]

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[20] These values should be viewed as absolute. They can be expected to vary within the LSO community and be adjusted from time to time.

Table 2-1. LSO-Based Performance Parameters

Primary States (position, speed)

Range:

verbal description	*symbol*	*value*
at the ramp	AR	100-600 ft from touchdown
in close	IC	600-2000 ft from touchdown
in the middle	IM	2000-4000 ft from touchdown
at the start	X	4000-5000 ft (~3/4 nm —beginning final leg)

Glideslope position:

verbal description	*symbol*	*value*	*meaning*
very high	$\underline{\text{H}}$	1.3°	well above FLOLS beam (~4 balls high)
high	H	0.8°	at upper visible limit of FLOLS beam
a little high	(H)	0.3°	in center of "one-ball-high" FLOLS indication
OK	OK	0	in center of "on-glideslope" FLOLS indication
a little low	(LO)	-0.3°	in center of "one-ball-low" FLOLS indication
low	LO	-0.8°	at lower visible limit of FLOLS beam
very low	$\underline{\text{LO}}$	-1.6°	well below FLOLS beam (~5 balls low)

Angle of Attack (Speed):

verbal description	*symbol*	*value*	*meaning*
very slow	$\underline{\text{SLO}}$	+3 units	nose-down chevron (green)
slow	SLO	+2 units	nose-down chevron (green)
a little slow	(SLO)	+1 units	donut + nose-down chevron (green)
OK	OK	0	donut, on-speed AOA
a little fast	(F)	-1 unit	donut + nose-up chevron (red)
fast	F	-2 units	nose-up chevron (red)
very fast	$\underline{\text{F}}$	-3 units	nose-up chevron (red)

Lineup Position:

verbal description	*symbol*	*value*	*meaning*
lined up very far rt	$\underline{\text{LUR}}$	3.5°	right of deck centerline
lined up right	LUR	2.5°	right of deck centerline
lined up a little right	(LUR)	1.5°	right of deck centerline
OK	OK	0	on deck centerline
lined up a little left	(LUL)	1.5°	left of deck centerline
lined up left	LUL	2.5°	left of deck centerline
lined up very far left	$\underline{\text{LUL}}$	3.5°	left of deck centerline

Secondary States (rate of change of position)

Sink Rate:

verbal description	*symbol*	*value*	*meaning*
not enough R/D	NERD!	0.8 °/sec	approx level flight @ 1000' range
not enough R/D	NERD	0.4 °/sec	approx level flight @ 2000' range
not enough R/D	NERD	0.2 °/sec	approx level flight @ 4000' range
not enough R/D	(NERD)	0.1 °/sec	
OK	OK	0	descending on GS
too much R/D	(TMRD)	-.1 °/sec	
too much R/D	TMRD	-.2 °/sec	
too much R/D	$\underline{\text{TMRD}}$	-.4 °/sec	

Drift Rate:

verbal description	*symbol*	*value*	*meaning*
very fast right drift	$\underline{\text{DR}}$	1.0 °/sec	~10° heading error at 1/4 nm
right drift	DR	0.5 °/sec	~5° heading error at 1/4 nm
a little right drift	(DR)	0.2 °/sec	~2° heading error at 1/4 nm
OK	OK	0	
a little left drift	(DL)		
left drift	DL		
very fast right drift	$\underline{\text{DL}}$		

Figure 2-6 shows a scale view of the glideslope and lineup ranges in terms of angular deviations from the nominal flightpath. This is intended to present a frame of reference for the magnitude of flightpath excursions (horizontal- and vertical-planes) as well as the precision expected. Note the relative range of FLOLS information presented to the pilot as indicated by the scale at the left.

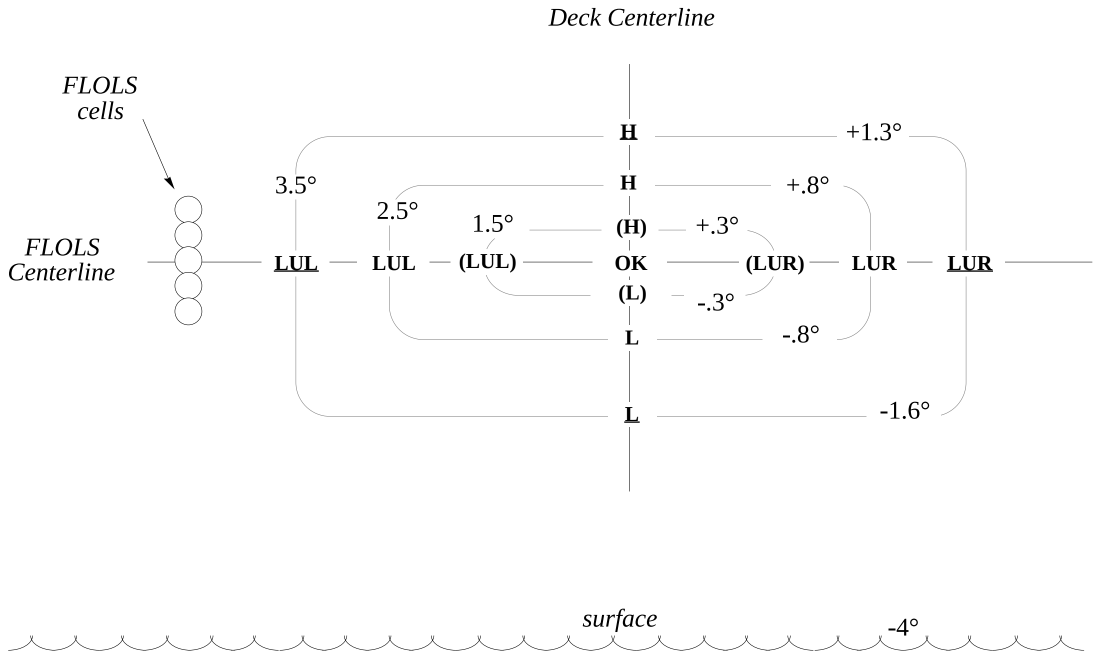


Figure 2-6. Scale Drawing of Approach Flightpath Parameters.

A corresponding planview of the approach geometry is given in Figure 2-7. This shows that the FLOLS becomes visible well before roll-out onto final, but the roll angle of the FLOLS light plane precludes valid glideslope information until on the centerline (which shall be explained shortly.)

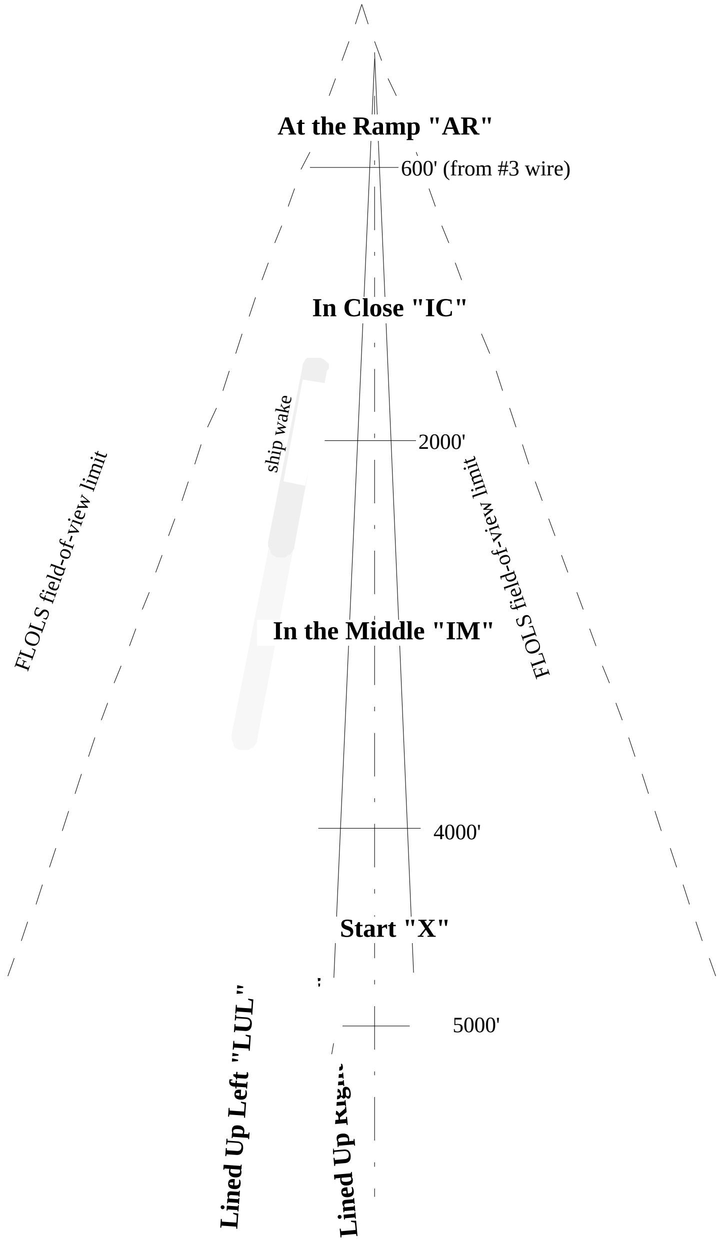


Figure 2-7. Planview of Final Approach Leg.

Figure 2-8 shows the geometry of the carrier deck. Dimensions are subject to minor variations depending upon the specific ship and are given in Reference 41.

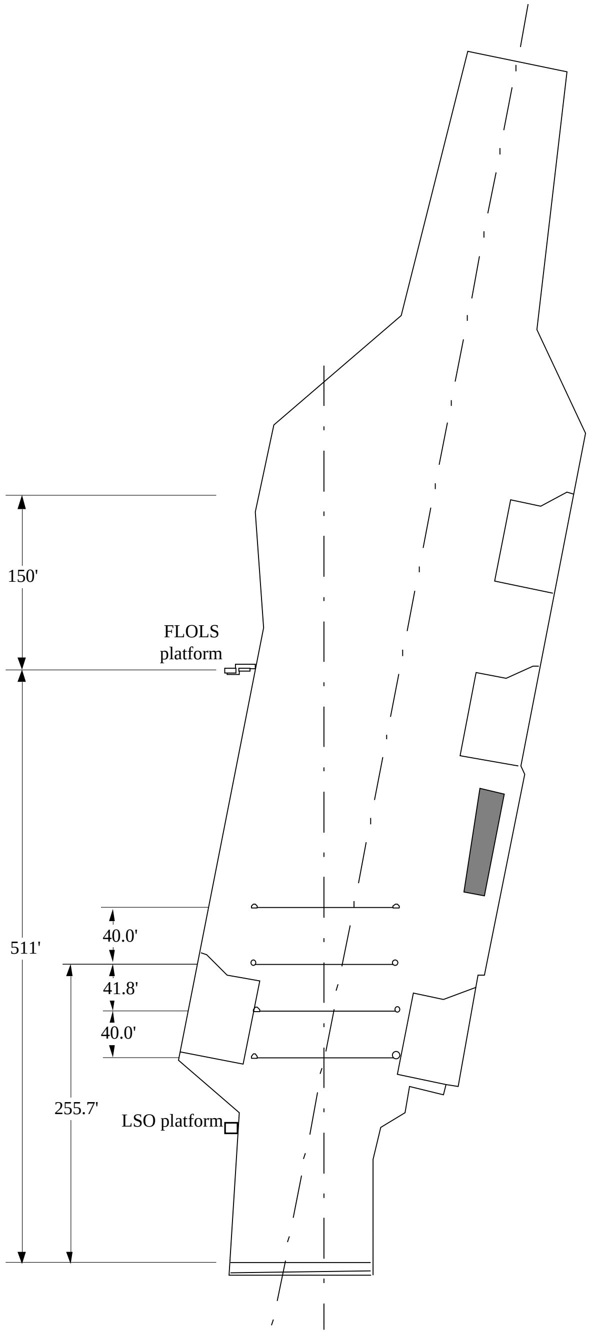


Figure 2-8. Planview of Carrier Deck.

2.1.3 LSO View of Outer-Loop Control

Table 2-2 presents a list of outer-loop control factors from the LSO's vantage point (Reference 45). These are useful in evaluating aspects of the task and of the aircraft which may be crucial to success. A number of these items are concerned with where on the final approach corrections can be made, especially when engine response is a factor.

According to this table, LSO's exercise may more caution with corrections from a high glideslope deviation than from low. Also, the aircraft should be stabilized on the approach by the "in-close" position (about 1/4 nm range).

Table 2-2. Outer-Loop Control Factors

Profile:

- More ramp strikes occur when the pilot is correcting for a high deviation in-close than for a low deviation.

- For significant multiple deviations in close, a waveoff should be used by the LSO. As a rule of thumb, if 2 major deviations (from among GS, LU, AOA or power) are AFU approaching the waveoff point, use waveoff. This is especially critical with a CQ pilot.

- For unsettled dynamics (speed, power, wing position, flight vector, pitch) in close, the LSO should consider giving a waveoff.

- High at the ramp with less than optimum rate of descent can lead to a dangerous long bolter. Do not hesitate to use waveoff.

- High at the ramp with excessive rate of descent can easily result in a hard landing.

- LSO should never accept a low trend on an approach.

- Be prepared for sink rate increases during late lineup corrections.

- LSO should no accept a high trend on an approach.

- Poor trends leading to the start and at the start are good indicators that the pass is going to be a problem due to pilot disorientation or poor pilot scan.

- A poor start frequently leads to overcontrol tendencies in the remainder of the pass.

- Be alert for the "moth effect" (drift left in-close or at-the-ramp) due to pilot fixation on the meatball at the expense of lineup control.

- During day recoveries, beware of pilot tendency to try to salvage an extremely poor start (i. e., <u>OSX</u>, NESA HFX, <u>HFX</u>, etc.). If not stable approaching in-close position, use waveoff.

- A major glideslope deviation at-the-start to in-the-middle is difficult for the pilot to salvage. Extra LSO assistance may be needed to help pilot get aboard.

- If calls are necessary for aircraft with slow engine response (A-7, S-3, F-14), they must be given well prior to glideslope interception when correction is being made for a high deviation.

- For airrcraft with excellent engine response(A-6, EA-6, F-4), be alert for pilot overcontrol of power. This also includes excessive power redu tions following too much power.

2.2 Aircraft Characteristics

A variety of fixed-wing aircraft types operate from carrier decks, including fighters, attack aircraft, trainers, anti-submarine aircraft, and transports. The purpose of this section is to describe the characteristics of a number of existing carrier aircraft in order to provide a feel for the values which may be of use in subsequent analysis.

Most of the aircraft which are represented in this section have successfully and satisfactorily operated from carriers. One feature of this study is to examine and understand the characteristics of these existing aircraft. First, some characteristics from the LSO's view are listed. Next, an array of computed characteristics are given which permit a comparison of aerodynamic, trim, and response parameters. Finally, some examples of engine response data are presented.

2.2.1 LSO View of Aircraft Characteristics

The Landing Signal Officer (LSO) is particularly sensitive to the outer-loop control aspects of carrier aircraft. Glideslope, angle of attack, and lineup are the primary concerns of the LSO during the final 3/4 nm approach to the ship.

Table 2-3 gives a brief sketch of carrier landing characteristics of several Navy airplanes based on the Reference 45 study of the LSO's duties. While the items mentioned are qualitative, they portray an overview of the various control axes for specific aircraft types.

Table 2-3a. Carrier Landing Features of Existing Aircraft—LSO View.

A-3:
Good power response.
Frequently drops nose on lineup correction to left.
Occasional yaw due to assymetric throttle control.
Lineup a little difficult to control due to size and long wingspan.
Tendency to go nose up on power increase, nose down on power decrease.
Will bounce on nose-down landing.
EA-3B is faster than KA-3B and is more sensitive to nose movement.
KA-3B tends to decel more than EA-3B.
Single-engine power response is adequate.

A-4:
Excellent lineup control.
Good power response.
Tendency for hook-skip bolter on nose-down landing and on rough wings (swinging hook).
Good speed stability.
Tendency for nose pitch up on waveoff.
When cocked-up, hard for pilot to see landing area.

A-6:
Excellent power and waveoff response, but easily over-controlled.
Tendency to settle on late lineup corrections.
Tendency for hook-skip bolters on noe-down landings.
KA-6 (tanker) is a little underowered.
Pilot visibility deficiencies result in frequent lineup control difficulties.
Single-engine is only a problem under conditions of high gross weight, high winds, high temperature, speedbrakes retracted.
Lineup control difficulties due to pilot visibility problems.
Frequently shows rough wings, but not always associated with lineup deviation.
Gliding approach and back on power if speedbrakes retracted.

EA-6B:
Excellent power and waveoff response.
Long fuselage and sensitive nose, therefore high in-flight engagement potential.
Tendency for hoo-skip bolters on nose-down landings.
Frequently described as similar to basic A-6.
Tendency for decel due to sensitive nose.
Has no speedbrakes, thus more back on pwer than A-6E.

A-7:
Slow engine response when back on power.
Nose movement is common during approach.
HIM frequently leads to SIC-AR; LOX-IM frequently leads to bolter.
LOB pass requires noe finesse to avoid bolter or ramp strike/hard landing.
AOA system and external AOA indicator lights fail frequently.
Loss of control augmentation results in heavy controls.
Loss of yaw augmentation results in yaw instability.
No-flap approach is much faster and well back on power.

Table 2-3b. Carrier Landing Features of Existing Aircraft—LSO View.

F-4:

Excellent power and waveoff response; also easy to overcontrol glideslope (up and down).

Glideslope control primarily with power, very little nose movement.

Stable AOA and nose.

Faster approach speed than others; high WOD requirements due to arresting gear engaging limits.

Fuel critical; frequently few looks before tanking or divert.

Must beware of HIC; can lead to hard landing due to ease of glideslope correction with power reduction.

Loss of BLC means very high approach speed.

Single engine approach done at half-flaps and speed is significantly increased; power response significantly degraded, burner needed for waveoff.

Lineup control is more difficult in F-4S model.

F-14:

Slow engine response after back on power.

Glideslope control uses coordinated power and nose.

Tendency to glide leading to decel, come-down.

Tends to SIC when "gliding" through burble.

Long fuselage, therefore in-flight engagement potential.

Hook-skip bolter potential on nose-down landings and for late lineup corrections at ramp.

Lineup critical due to long wingspan.

Without DLC engaged, aircraft is back on power.

Single-engine—speedbrake retracted, no problem except that pilot must work very hard.

No-flaps—higher speed, no problem.

F/A-18:

Excellent power and waveoff response..

Flat attitude when on AOA.

If back on power and cocked-up, SIC-AR is probable.

Easy to over-rotate on waveoff; in-flight engagement potential.

Nose adjustments must be coordinated with power changes to get glideslope correction results.

T-2:

Excellent power and waveoff response.

Glideslope control involves coordinated power and nose.

Can get nose pitch up with large power addition.

Tendency to hook-skip bolter on nose-down lading and late lineup (swinging hook).

Single-engine has good power response.

Table 2-3c. Carrier Landing Features of Existing Aircraft—LSO View.

S-3:
Slow engine response when back on power.
Tendency to "glide" during approach.
DLC is good for correcting high deviation and avoiding an undesired power reduction.
Without DLC system, nose pitch is sensitive to power changes.
Difficulties with burble under high WOD conditions.
Burble causes glideslope control difficulties.
Lineup control difficult, especially with shifting wind conditions.
Nose pitch is sensitive to power changes, especially with DLC failure.
No flap—very fast and well back on power.
Single-engine—half-flaps, lineup control difficulties due to asymmetric thrust.

C-1:
Nearly instantaneous power response.
On the "cut" signal takes "high-dip" to land.
Single-engine is faster, no flare on touchdown; no problem.

C-2:
Like E-2, except thant when very light there is tendency to float during approach.

E-2:
Excellent power and waveoff response.
Excessive power reduction can "flatten" prop enough to cause a rapid settle.
Lineup control difficult; also very critical due to long wing span.
Long fuselage, therefore high in-flight engagement potential.
Glideslope control very sensitive to nose movement.
Fuselage alignment lights (when visible) and "popping sound" indicate need for right rudder.
Tendency for hook-skip bolter on nose-down landing.
On single engine approach, lineup control is difficult; also decel must be avoided.
Lineup is extremely critical (±2.5 ft) on barricade recovery.
On no-flap approach, very cocked-up and hook-to-ramp clearance is reduced.

2.2.2 Characteristics of Existing Aircraft

This section provides a concise summary of characteristics for several existing aircraft which are central to outer-loop control. These characteristics correspond to those which will be discussed in Section 3 and will be used for the analyses in Section 4.

The following figures employ a standard format to portray a range of aerodynamic, trim, and response parameters. This permits one to make direct comparisons easily.

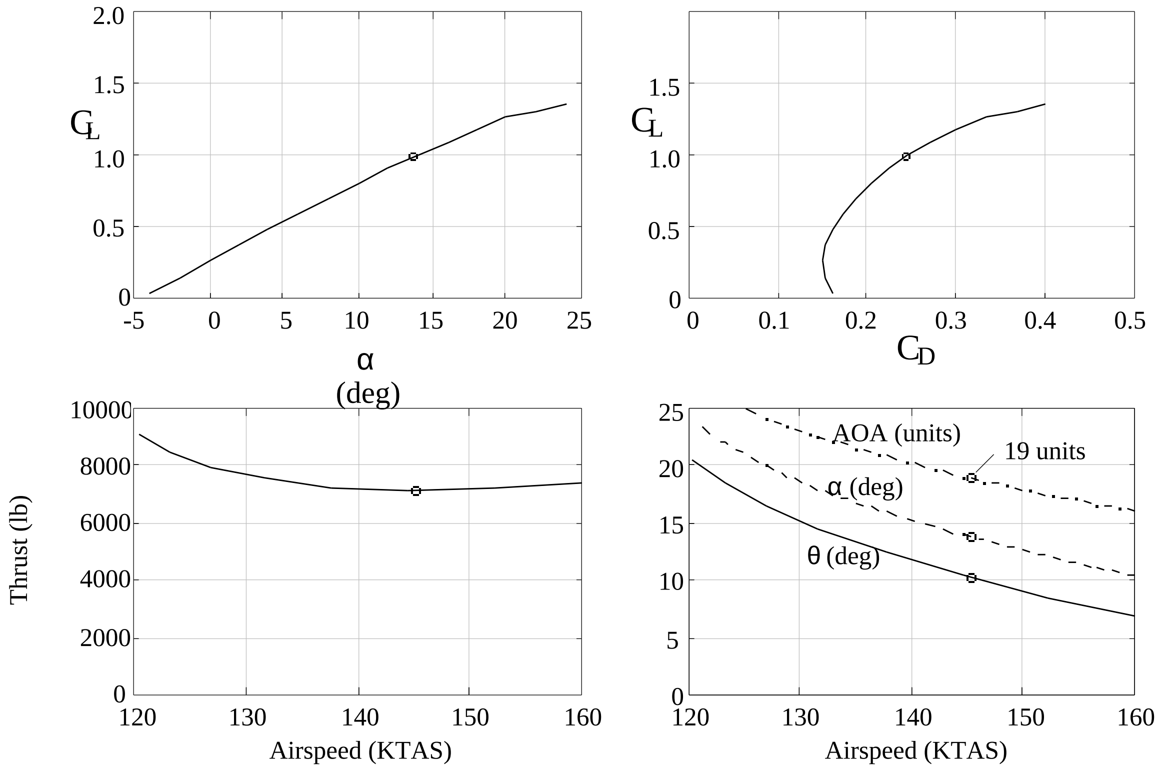
The configuration of each aircraft consists of a single gross weight, usually the maximum carrier landing weight, a representative center of gravity, gear down, and flaps set for power approach. The flightpath angle is -3.5° in each case. Parameter variations are shown for a range of speeds along with an indication of the nominal approach speed.

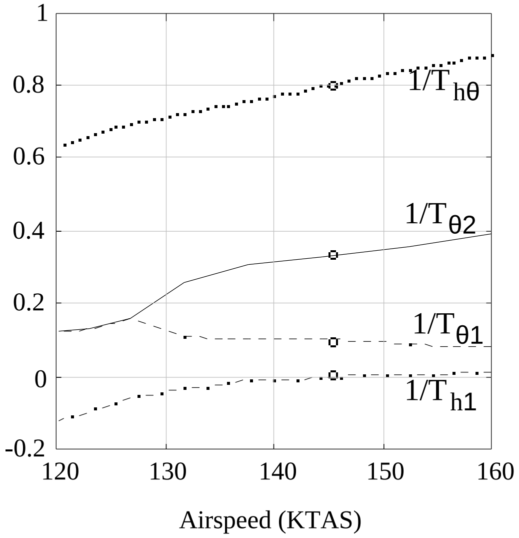
Aerodynamic data consist of the trimmed lift and drag coefficients for the configuration noted. These data are the basis for computing the trim thrust, pitch attitude, and angle of attack. Where information was available, the indicated angle of attack (AOA) is also shown. Finally, response-parameter plots show the transfer function factors $1/T_{\theta_1}$, $1/T_{\theta_2}$, $1/T_{h_1}$, and $1/T_{h\theta}$. As Section 3 explains, these factors are fundamental to the response of flightpath and angle of attack.

Figures 2-9 to 2-18 present plotted data for the following aircraft:

- F-4J (equipped with BLC)
- F-8C
- F-8J (equipped with BLC)
- F-14D (20° sweep)
- F/A-18A
- F-111B (16° sweep)
- A-3B (standard-wing version)
- RA-5C
- A-6E
- T-45A (based on initial aerodynamic data package)

These plots are based on manufacturers' data where available (References 47 through 50). References 12 and 51 through 53 are used as secondary sources. These aircraft represent some of the standard fleet carrier aircraft which have operated over the past thirty years and several of which are in current use. The F-111B was never operational but did make several carrier landings and underwent Navy Preliminary Evaluation testing. The T-45A is still under development at this time and the aerodynamic data used here are in the process of revision.



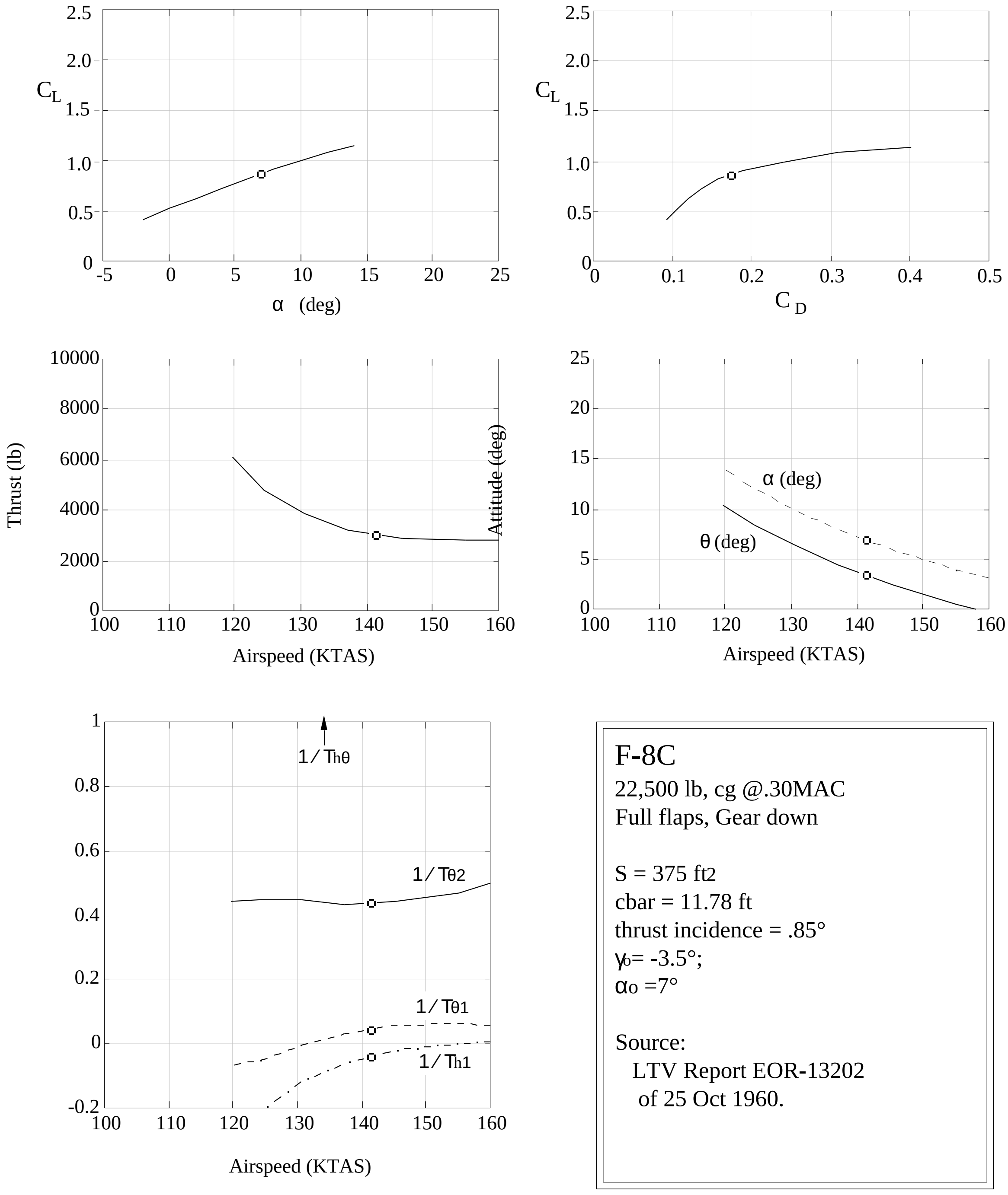


F-4J
40,000 lb, cg @.33MAC
Full flaps, BLC, gear down

S = 530 ft2
cbar = 192.5 in
thrust incidence = 5.25°
γ_o= -3.5°;
Wt = 40000 lb
α_o =13.8° , 19 units (Target AOA)
AOA = 7.4 + 0.84 · α

Source:
Trimmed Aero Data from
MDC 9842, p 4.39 1 Dec 64.

Figure 2-9. Summary of F-4J Aero, Trim, and Response Parameters.

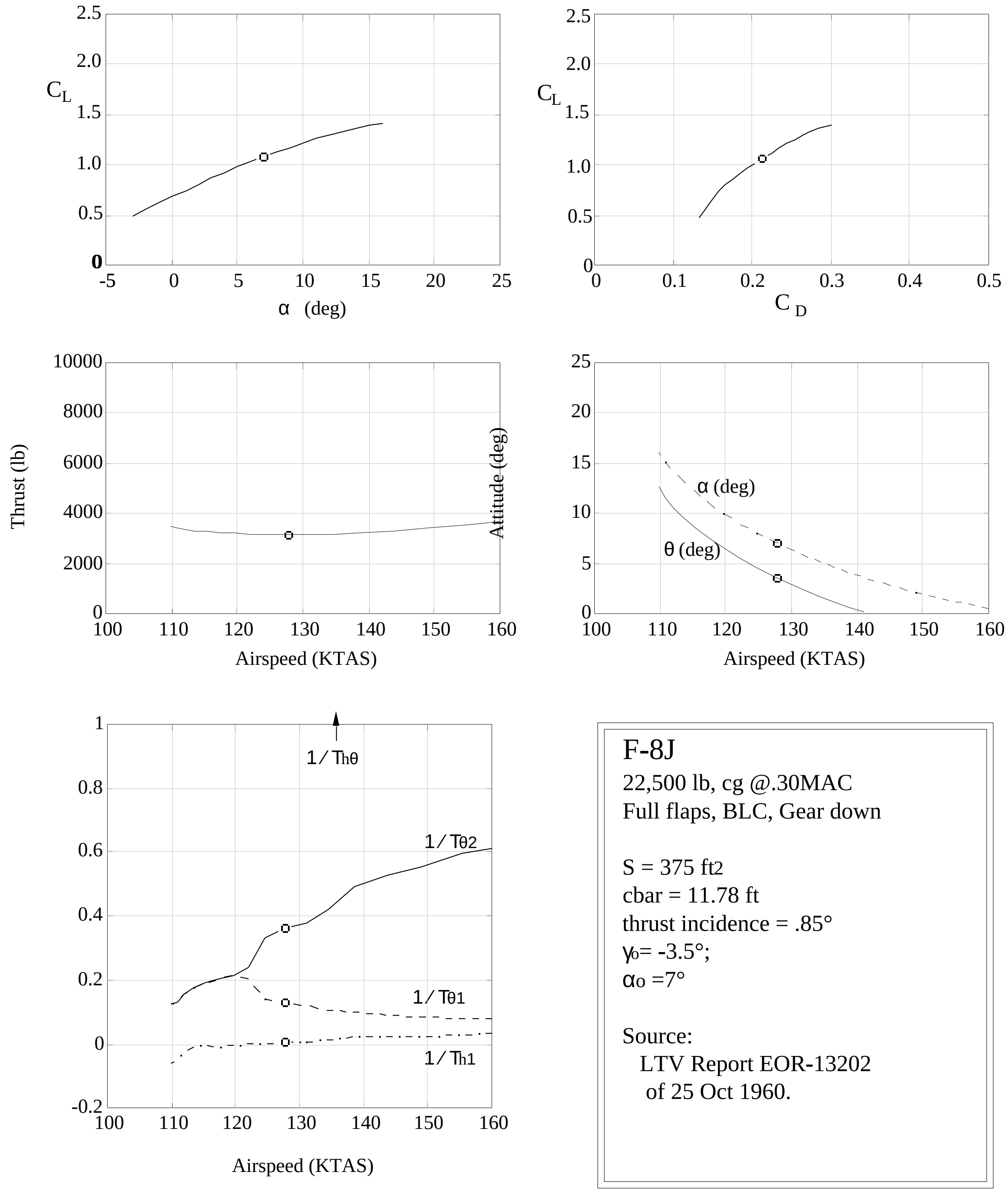


F-8C
22,500 lb, cg @.30MAC
Full flaps, Gear down

S = 375 ft^2
cbar = 11.78 ft
thrust incidence = .85°
γ_0= -3.5°;
α_0 =7°

Source:
LTV Report EOR-13202
of 25 Oct 1960.

Figure 2-10. Summary of F-8C (no BLC) Aero, Trim, and Response Parameters.

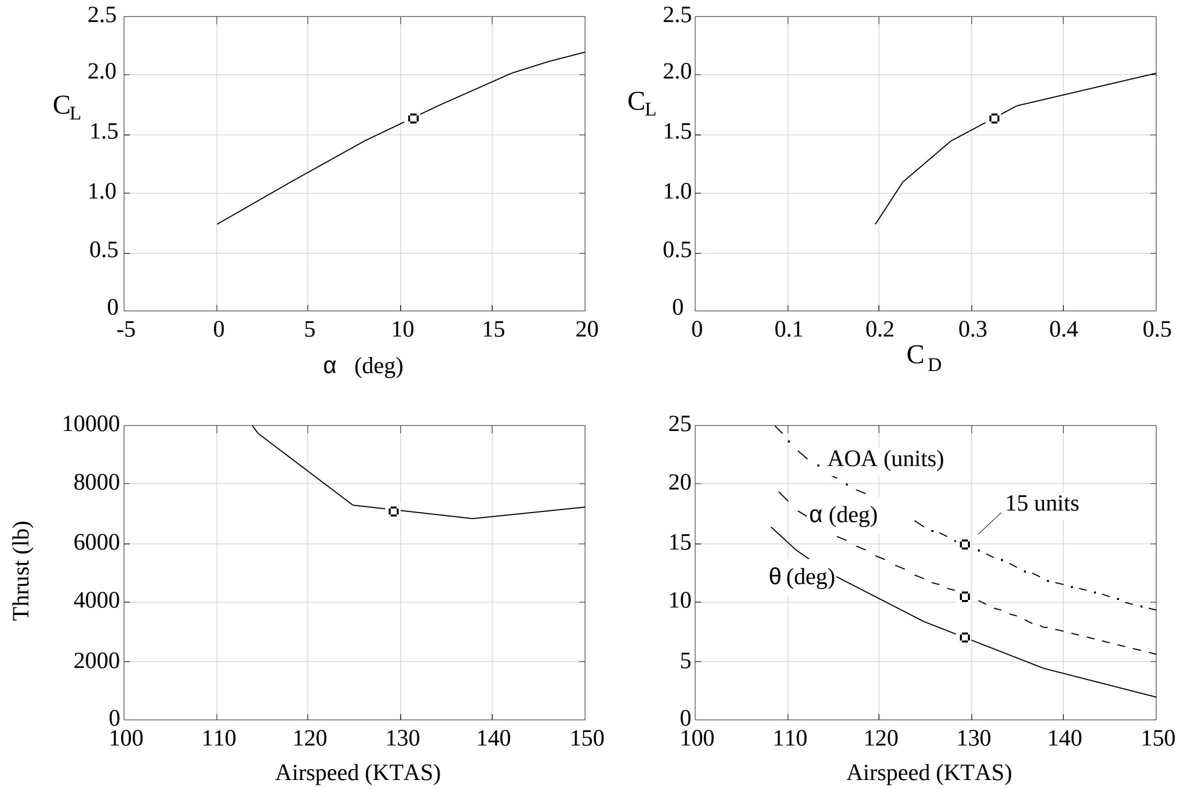


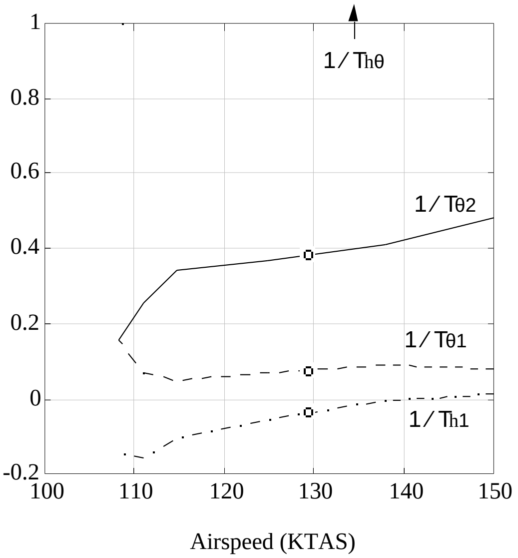
F-8J
22,500 lb, cg @.30MAC
Full flaps, BLC, Gear down

S = 375 ft^2
cbar = 11.78 ft
thrust incidence = .85°
γ_0= -3.5°;
α_0 =7°

Source:
LTV Report EOR-13202
of 25 Oct 1960.

Figure 2-11. Summary of F-8J (BLC) Aero, Trim, and Response Parameters.





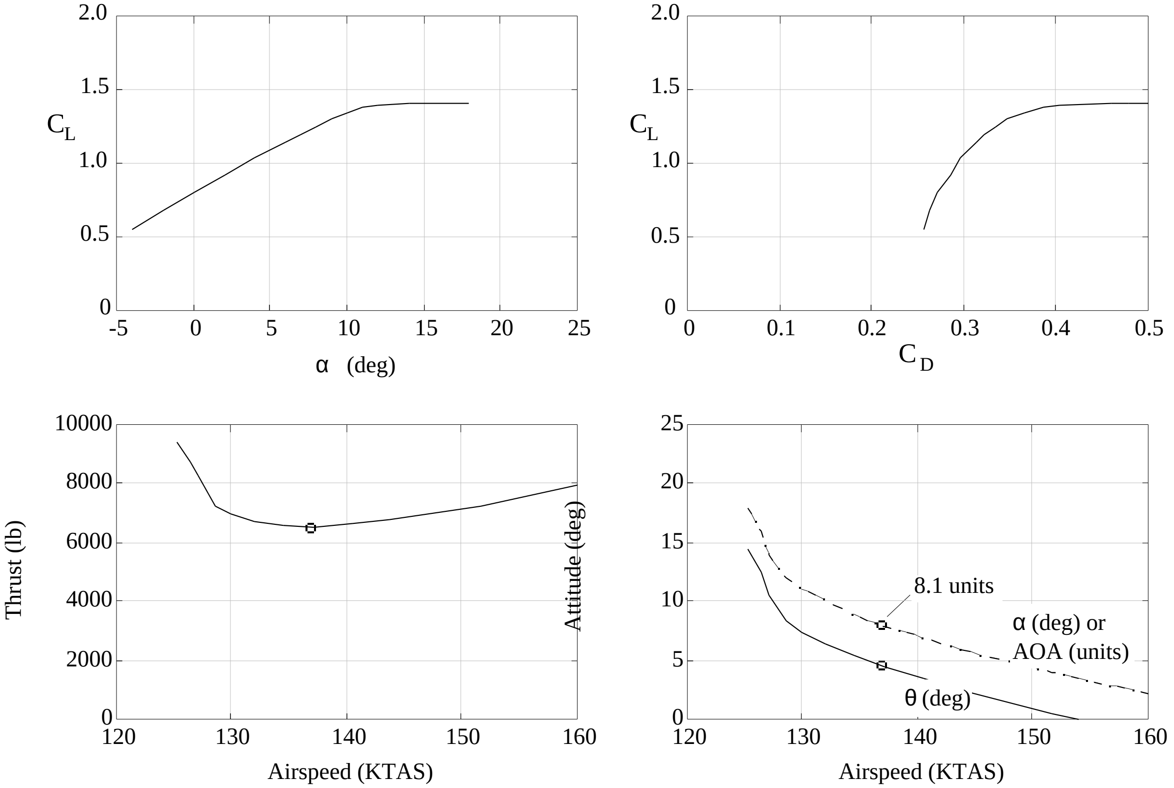
F-14D

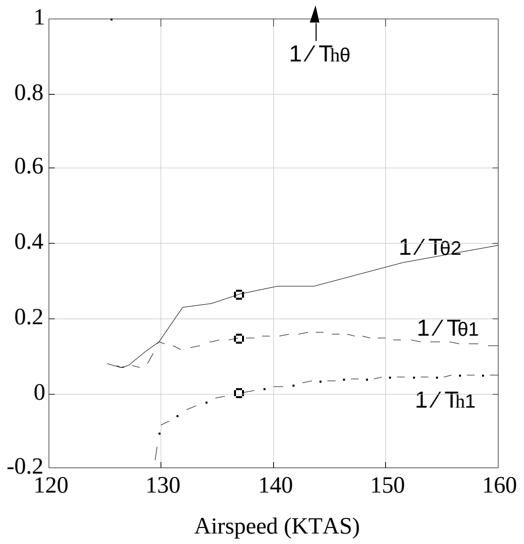
54,000 lb, cg @.162MAC
Full flaps, DLC, gear down

$S = 565$ ft^2
cbar = 117.62 in
thrust incidence = 0.735°
$\gamma_o = -3.5°$;
$\alpha_o = 10.64°$, 15 units (Target AOA)
$AOA = 3.3 + 1.1 \cdot \alpha$

Source:
Trimmed Aero Data from
Grumman Rpt A55-350-R-85-17,
28 June 1985.

Figure 2-12. Summary of F-14D Aero, Trim, and Response Parameters.

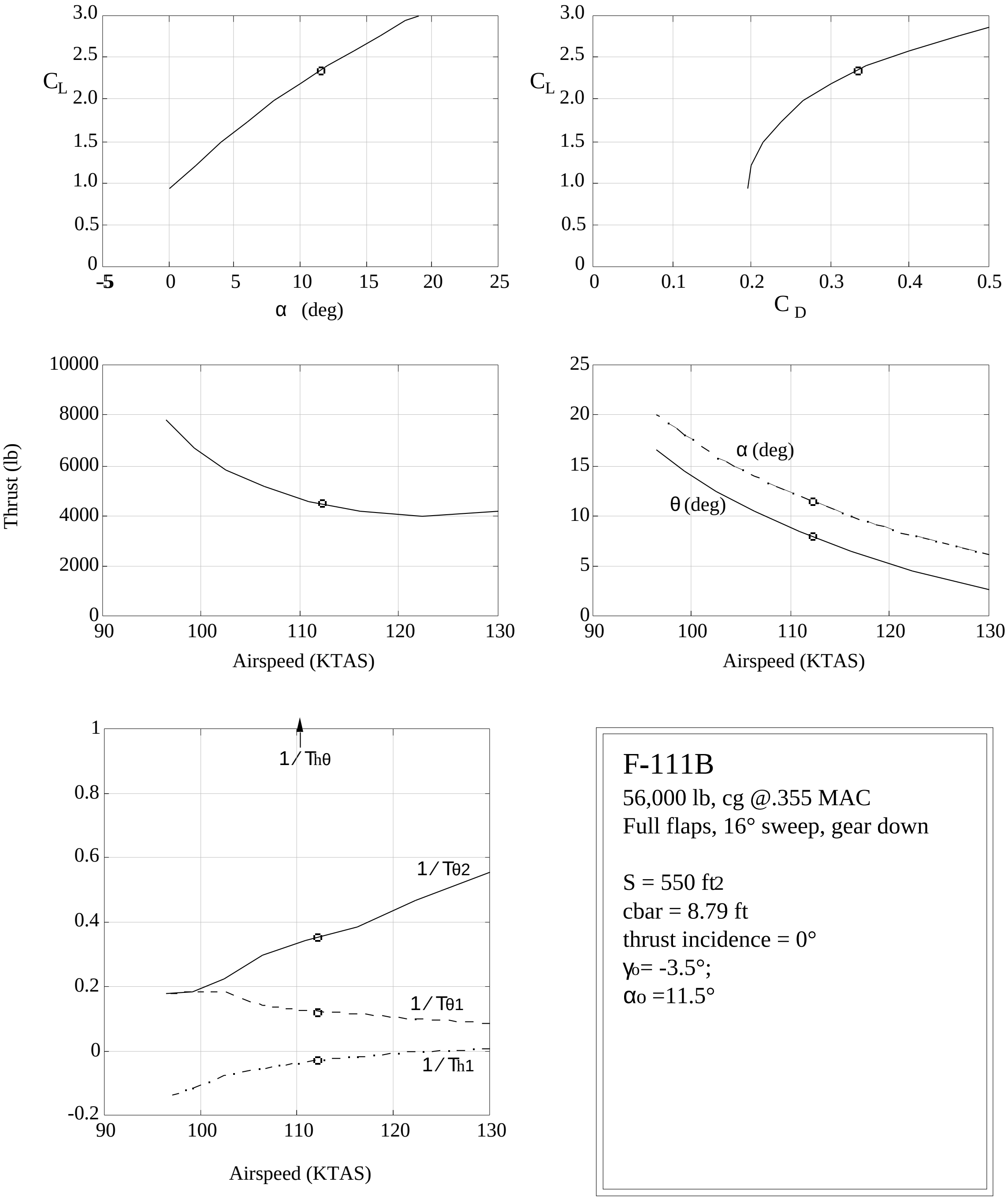




F/A-18A
33,000 lb, cg @.25MAC
Full flaps, gear down
Fighter Escort--2 AIM-7, 2 AIM-9
$\delta_{f/a}$, δ_h, δ_r toe-in, on AOA schedule
S = 400 ft^2
cbar = 11.52 ft
thrust incidence = 0°
γ_0= -3.5°;
α_0 =8.1° , 8.1 units (Target AOA)
AOA = 0 + 1.0 · α

Source:
Trimmed Aero Data from
MDC A8575 p 3-121 31 Mar 84.

Figure 2-13. Summary of F/A-18A Aero, Trim, and Response Parameters.



F-111B

56,000 lb, cg @.355 MAC

Full flaps, 16° sweep, gear down

$S = 550\ ft^2$

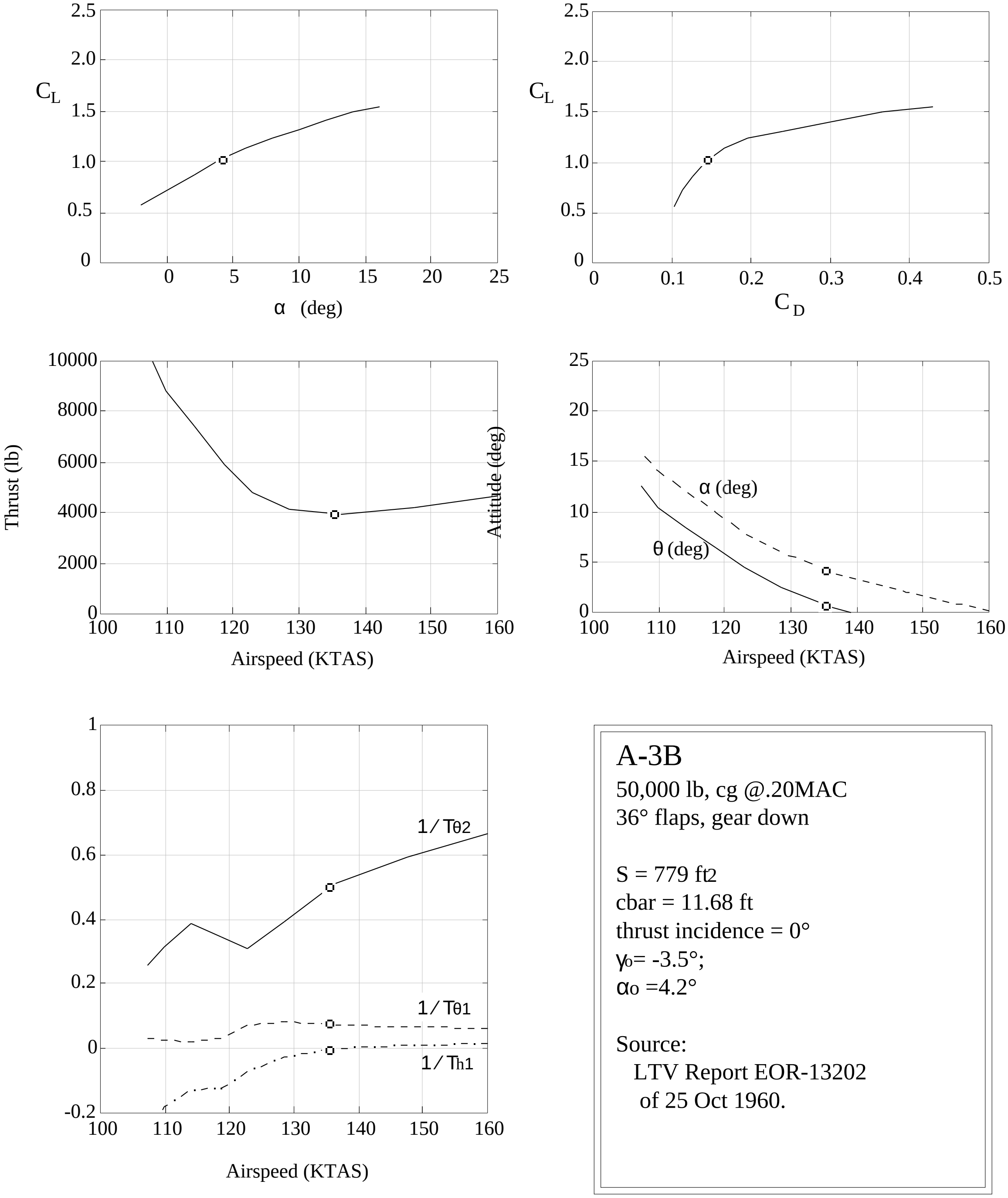
cbar = 8.79 ft

thrust incidence = 0°

$\gamma_o = -3.5°$;

$\alpha_o = 11.5°$

Figure 2-14. Summary of F-111B Aero, Trim, and Response Parameters.



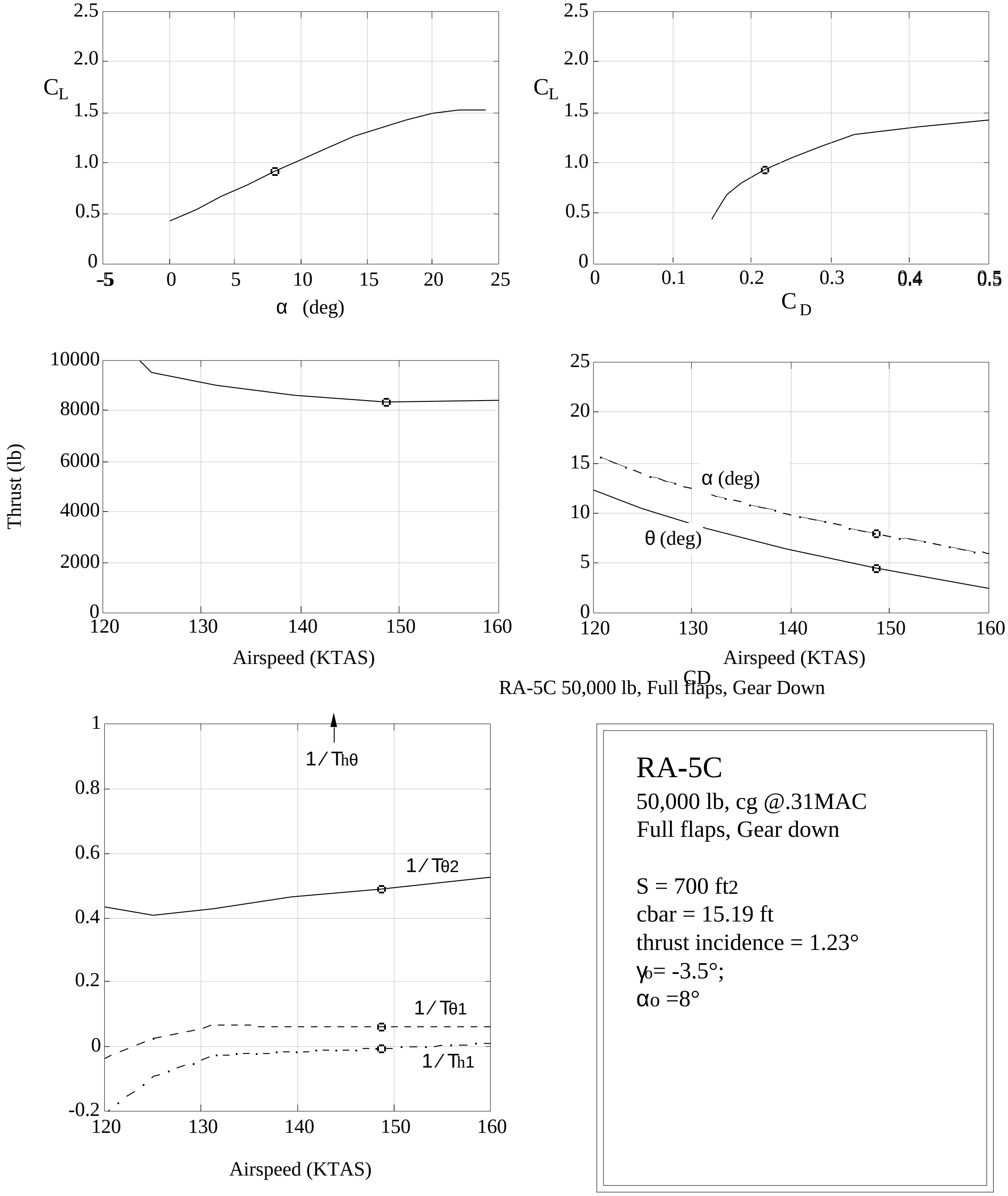
A-3B

50,000 lb, cg @.20MAC
36° flaps, gear down

S = 779 ft^2
cbar = 11.68 ft
thrust incidence = 0°
γ_0= -3.5°;
α_0 =4.2°

Source:
LTV Report EOR-13202
of 25 Oct 1960.

Figure 2-15. Summary of A-3B Aero, Trim, and Response Parameters.



RA-5C

50,000 lb, cg @.31MAC

Full flaps, Gear down

$S = 700\ ft^2$

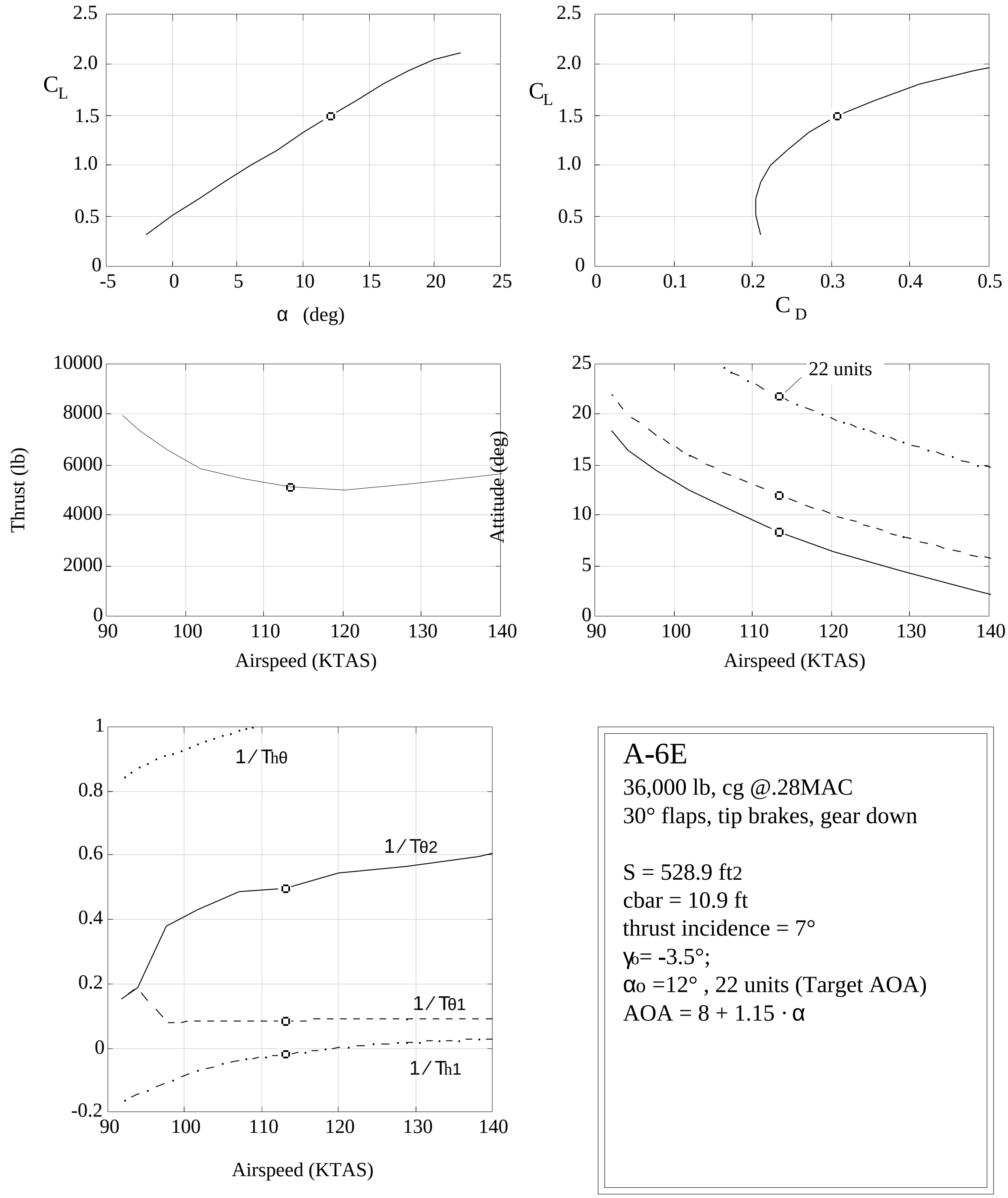
cbar = 15.19 ft

thrust incidence = 1.23°

$\gamma_o = -3.5°$;

$\alpha_o = 8°$

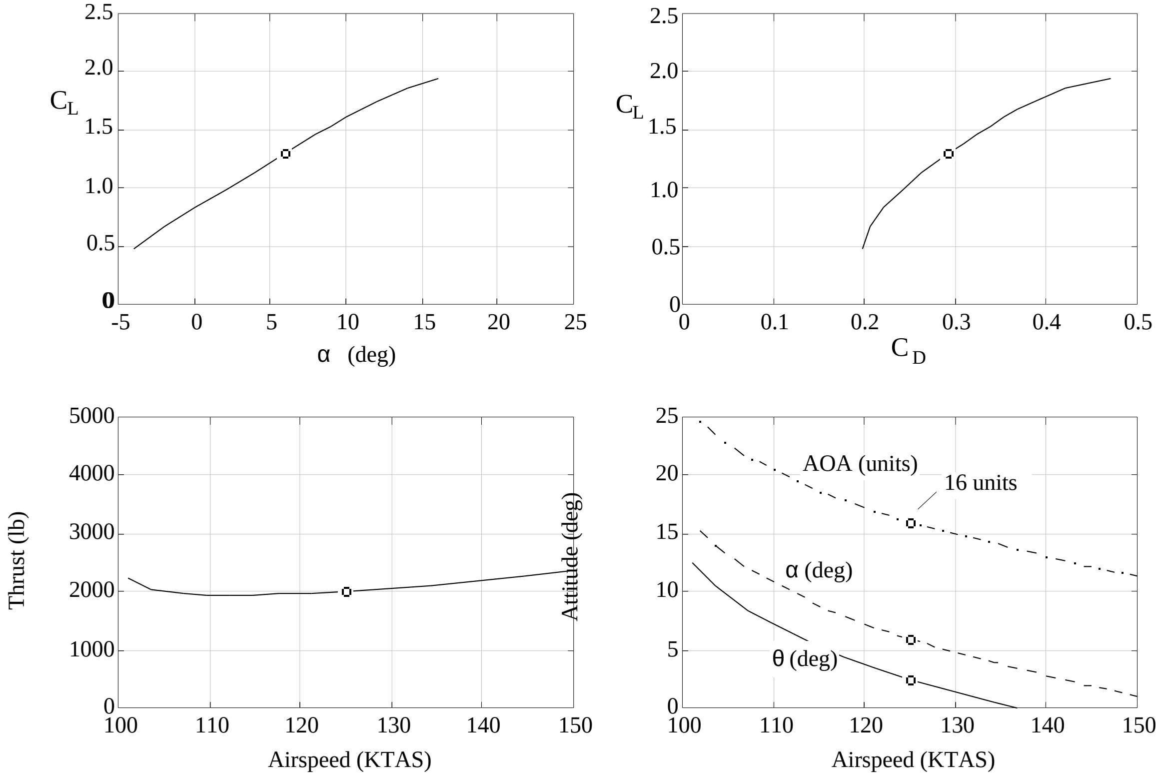
Figure 2-16. Summary of RA-5C Aero, Trim, and Response Parameters.

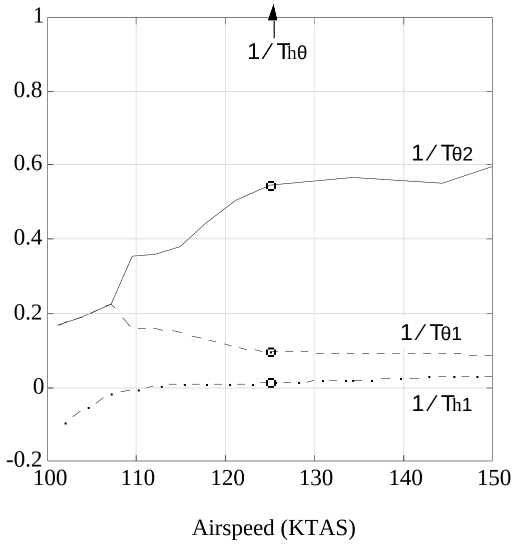


A-6E
36,000 lb, cg @.28MAC
30° flaps, tip brakes, gear down

S = 528.9 ft^2
cbar = 10.9 ft
thrust incidence = 7°
γ_0= -3.5°;
α_0 =12° , 22 units (Target AOA)
AOA = 8 + 1.15 · α

Figure 2-17. Summary of A-6E Aero, Trim, and Response Parameters.





T-45A

12,700 lb, cg @.25MAC
Full flaps, gear down

S = 179.64 ft^2
cbar = 69.96 in
thrust incidence = 0°
γ_o= -3.5°;
α_o =6° , 16 units (Target AOA)
AOA =10.35 + 0.94 · α

Source:
Trimmed Aero Data from MDC K2090 pp D23, D41 21 Nov 84.

Figure 2-18. Summary of T-45A Aero, Trim, and Response Parameters.

Other Aircraft Data

Table 2-4 provides additional characteristics for a variety of carrier aircraft at their nominal approach speeds. These data have been refined with the assistance of NAVAIR personnel (Reference 54). Most cases represent the NATOPS-prescribed approach speed.

Table 2-4. Outer-Loop Characteristics for Several Navy Carrier Aircraft.

Aircraft	*Weight*	*Speed*	*Alpha*	*CL*	*CD*	*CLα*	*∂ CD/∂ CL*	X_u	X_w	Z_u	Z_w	n_{z_α}†	$1/T_{\theta 2}$	$1/T_{\theta 1}$	$1/T_{h1}$
F-4J	40000	145	13.8	0.99	0.243	2.72	0.239	-0.064	0.045	-0.26	-0.39	3.0	0.35	0.11	0.01
F-8C	22500	141	7.0	0.87	0.174	2.65	0.362	-0.054	-0.014	-0.27	-0.44	3.2	0.45	0.04	-0.04
F-8J (BLC)	22500	128	7.0	1.06	0.213	2.86	0.200	-0.060	0.069	-0.30	-0.43	2.9	0.36	0.13	0.00
F-14D(DLC)	54000	129	10.6	1.65	0.323	4.30	0.317	-0.058	0.026	-0.30	-0.41	2.8	0.39	0.08	-0.03
F/A-18	33000	137	8.1	1.26	0.334	2.84	0.269	-0.074	0.055	-0.28	-0.35	2.5	0.27	0.15	0.01
F-111B††	56000	113	11.5	2.35	0.334	5.74	0.237	-0.048	0.071	-0.34	-0.44	2.6	0.36	0.12	-0.03
A-3B	50000	135	4.2	1.02	0.144	3.80	0.153	-0.040	0.061	-0.28	-0.55	3.9	0.51	0.08	0.00
A-4E	14500	130	13.0	0.98	0.230	3.30	0.250	-0.069	0.024	-0.29	-0.53	3.6	0.51	0.08	0.00
RA-5C	50000	149	8.0	0.93	0.216	3.47	0.252	-0.059	0.008	-0.26	-0.51	4.0	0.50	0.06	0.00
A-6E	36000	113	12.0	1.49	0.307	4.57	0.267	-0.069	0.031	-0.34	-0.55	3.3	0.53	0.09	-0.01
A-7E	22721	121	12.5	1.22	0.203	3.95	0.201	-0.052	0.055	-0.31	-0.54	3.4	0.50	0.09	-0.01
E-2C	42090	100	8.0	1.77	0.190	7.03	0.150	-0.041	0.077	-0.38	-0.78	4.1	0.73	0.08	-0.01
TF-9J	16500	125	10.0	0.92	0.184	3.27	0.210	-0.061	0.039	-0.30	-0.57	3.8	0.55	0.09	0.00
T-2C	12000	107	8.5	1.20	0.250	4.38	0.192	-0.074	0.053	-0.36	-0.69	3.9	0.65	0.11	0.01
TA-4J	14500	130	13.0	0.98	0.230	3.30	0.250	-0.069	0.024	-0.29	-0.53	3.6	0.51	0.08	0.00
T-45A	11253	123	5.0	1.22	0.270	4.13	0.160	-0.069	0.071	-0.31	-0.56	3.6	0.51	0.12	0.02
FJ-3	13678	112	11.5	1.06	0.188	3.44	0.152	-0.060	0.086	-0.34	-0.58	3.4	0.52	0.12	0.01
F4D-1	16870	121	18.0	0.56	0.107	1.80	0.342	-0.060	-0.016	-0.31	-0.54	3.4	0.55	0.05	-0.04
F7U-3	21030	133	16.0	0.69	0.140	2.55	0.165	-0.058	0.056	-0.29	-0.56	3.9	0.52	0.09	0.01
F9F-6	13440	114	9.8	1.02	0.198	3.95	0.260	-0.065	-0.001	-0.33	-0.68	4.1	0.68	0.06	-0.02
T-33A *	12000	125	3.9	0.96	0.130	5.07	0.120	-0.041	0.056	-0.30	-0.83	5.4	0.80	0.06	0.01
T-38A*	11761	180	5.8	0.63	0.137	2.87	0.260	-0.046	-0.020	-0.21	-0.51	4.8	0.51	0.04	-0.01
F-16*	18825	129	13.2	1.07	0.207	4.07	0.340	-0.057	-0.043	-0.30	-0.59	4.0	0.61	0.03	-0.04

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*USAF—not carrier aircraft.

† Trimmed values.

† † V_{PAmin} approach speed

Table 2-5 gives a comparison of carrier suitability for a variety of Navy aircraft, most of which are no longer in service. Nevertheless this can be used to correlate with some of the control factors that will be discussed in Sections 3 and 4.

Table 2-5. Carrier Suitability Rating Matrix

	Speed/Power Stability			Longitudinal Control		
position on aircraft	*slope on CD curve*	*engine CD curve*	*response*	*power*	*mechanical damping*	*characteristics*
A-3	2	3	3	4	3	2
A-4	5	5	4 (2)	4	3	4
RA-5C	2	2	4 (3)	2	4	3
A-6	3	4	4	3	3	3
A-7	4	4	2	4	3	5
F-3	(4)	(2)	(3)	(4)	(4)	(3)
F-4	4	4	5	4	4	2
F-8	1	1	2	3	3	1

	Lateral Control			Waveoff		
aircraft	*power*	*mechanical damping*	*engine characteristics*	*excess acceleration*	*rotation thrust*	*requirement*
A-3	3	1	2	3	4	4
A-4	3	4	4	4 (3)	4	4
RA-5C	3	2	1	5 (3)	2	1
A-6	2	3	4	4	5	4
A-7	4	4	5	2	4	3
F-3	(4)	(4)	(4)	(3)	(2)	(3)
F-4	4	4	4	5	4	3
F-8	4	2	3	3 (2)	3	2

		General		
aircraft	*approach size*	*single speed*	*field of engine*	*view*
A-3	2	3	2	(3)
A-4	5	3	-	(3)
RA-5C	2	1	2	(3)
A-6	3	5	4	(4)
A-7	5	3	-	-
F-3	(4)	(3)	-	(5)
F-4	3	2	5	(3)
F-8	4	4 (1)	-	(2)

rating	*values*
5	best
4	good
3	fair
2	poor
1	unsatisfactory

References: Basic table entries are from NAVAIR 51-35-501, those in parentheses from NATC FT2211 (Reference 25). Where there is a difference both values are given.

Table 2-6 lists the hook-to-eye distances for a number of Navy carrier aircraft. Personnel aboard the ship apply these dimensions in rigging the FLOLS prior to the recovery of each aircraft type.[21]

Table 2-6. Hook-to-Eye Distances for Several Navy Aircraft.

aircraft	*configuration*	*hook-to-eye distance*
A-3B	normal	17.25 ft
A-4A/B	full flaps	15.50
A-4C/E/F/L	full flaps	15.50
TA-4F/J	full flaps	16.25
RA-5C	50° flaps	16.00
A-6	flaps extended	16.75
EA-6B	30° flaps/slats extended	18.75
A-7	full flaps	14.50
F-4	full and half flaps	18.75
F-8H/K/L	wing up	13.25
F-8J	wing up,BLC on	13.25
F-8J	wing up,BLC off	13.25
F-14A	normal	19.70
E-2	normal	15.00
E-2	10° flaps	17.40
C-1A	normal	16.50
C-2A	30° flaps	15.00
S-2D/E	full flaps	16.50
S-3A	35° flaps	15.00

---

[21] These values are related to the FLOLS roll angle setting as described in Section 3.

2.2.3 Engine Dynamics

The engine response can contribute to the difficulty in controlling flightpath and airspeed. The lag in thrust response is a particularly important issue for several carrier aircraft with turbofan engines. For this reason the following data are presented in order to show how the effective first-order lag time constant (rise-time-to-63%) can vary with engine type and with the magnitude of the thrust command.

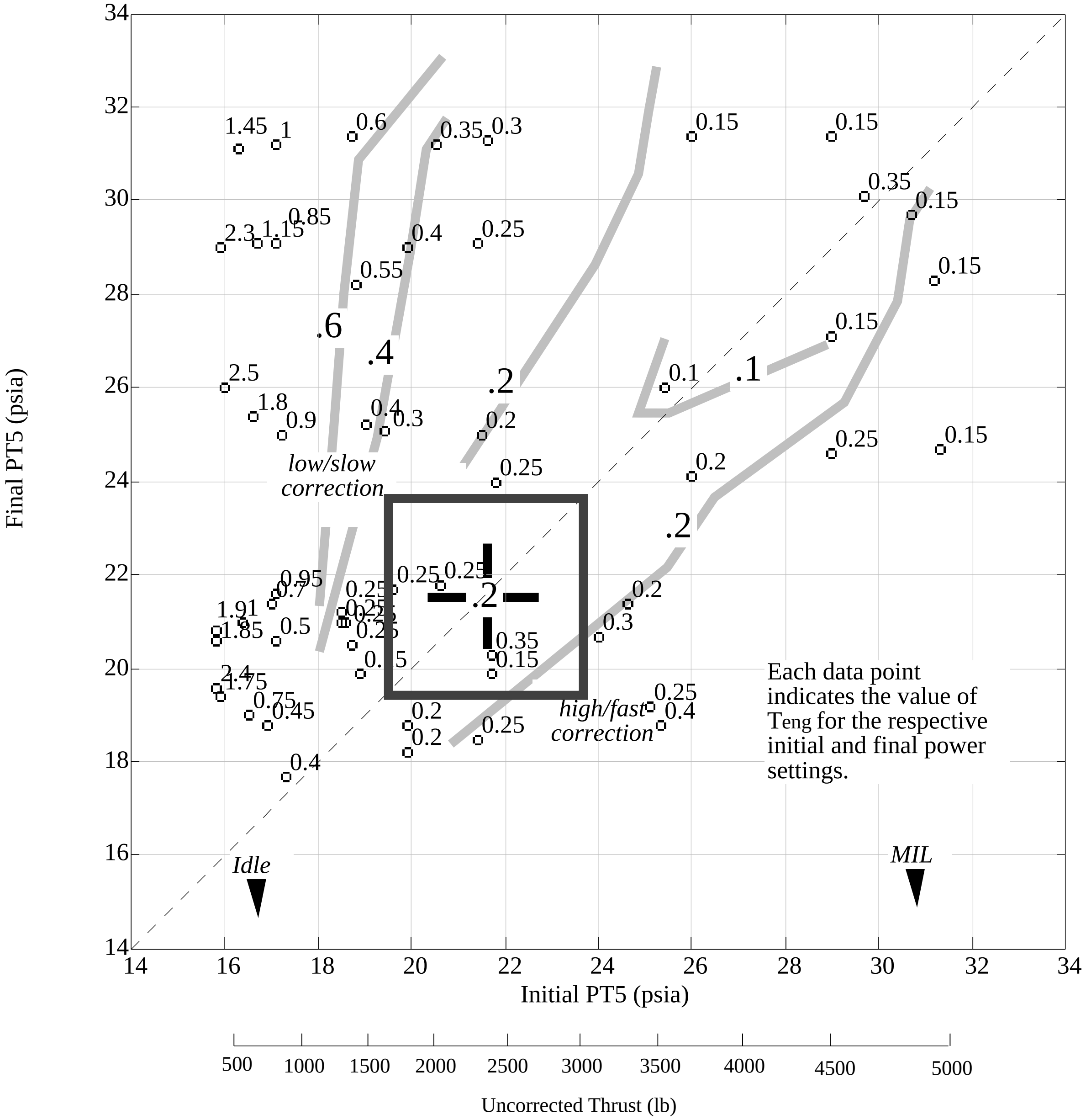
The Naval Air Test Center (NATC) supplied the engine response data shown in Figures 2-19 through 2-21 (Reference 55) as a result of recent measurements for several jet trainer aircraft. They include the J85, J52, and F405 engines. The first two are conventional turbojet engines found on the T-2C and TA-4J, respectively. The F405 engine is a high-bypass-ratio turbofan used on the T-45. (One version of the J52 is also installed in the A-6).

Figures 2-19 through 2-21 show engine-lag contours (T_{eng}) for sets of initial power setting and final power setting. The small box in the center represents the operating range corresponding to ± 3.5° $\Delta\gamma$.

For a nominal thrust setting in each of the three aircraft, the effective engine lags for a step change in throttle were measured to be:

engine	*Teng*
F405-RR-400A	0.56 sec
J52-P-8	0.30
J85-GE-4A	0.20

Each engine has substantially longer effective engine lag as the thrust is increased from a setting below the nominal approach value. This would correspond to corrections from low on the glideslope or from a slow condition. The high-bypass-ratio turbofan is also the most critical in this regard.



Each data point indicates the value of Teng for the respective initial and final power settings.

Figure 2-19. Thrust Lag Data for the J85 Engine (T-2C).

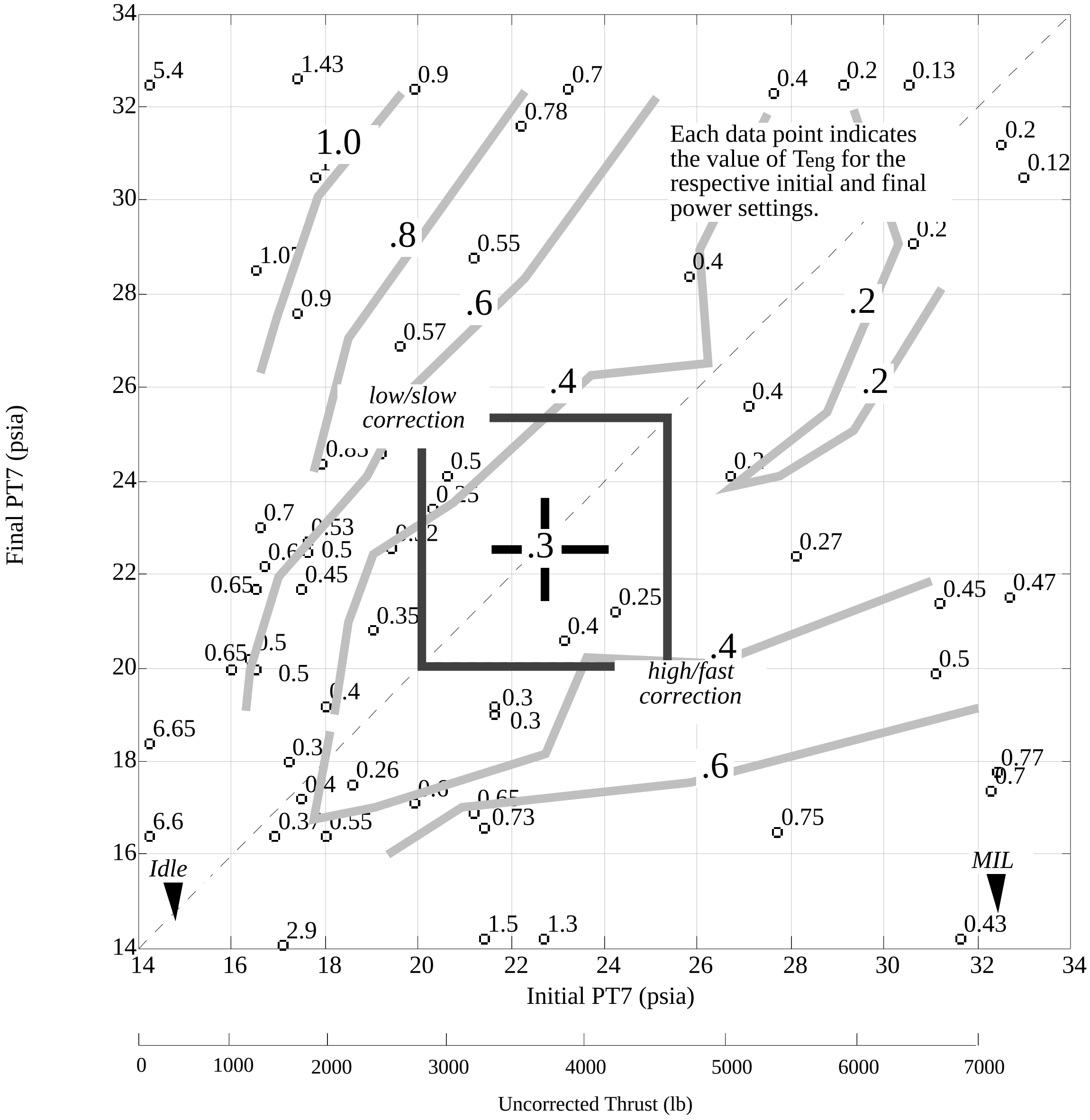


Figure 2-20. Thrust Lag Data for the J52 Engine (TA-4J).

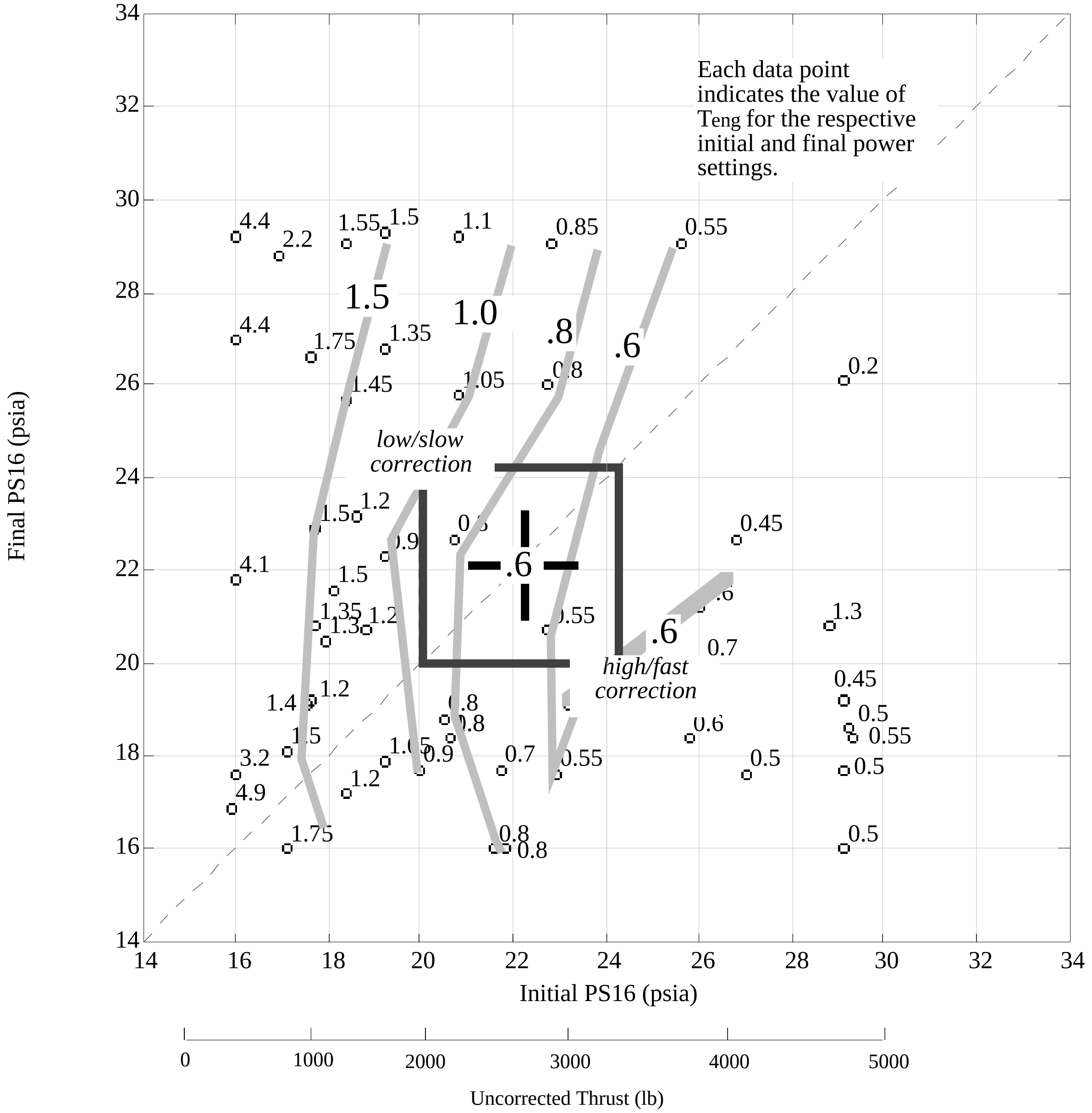
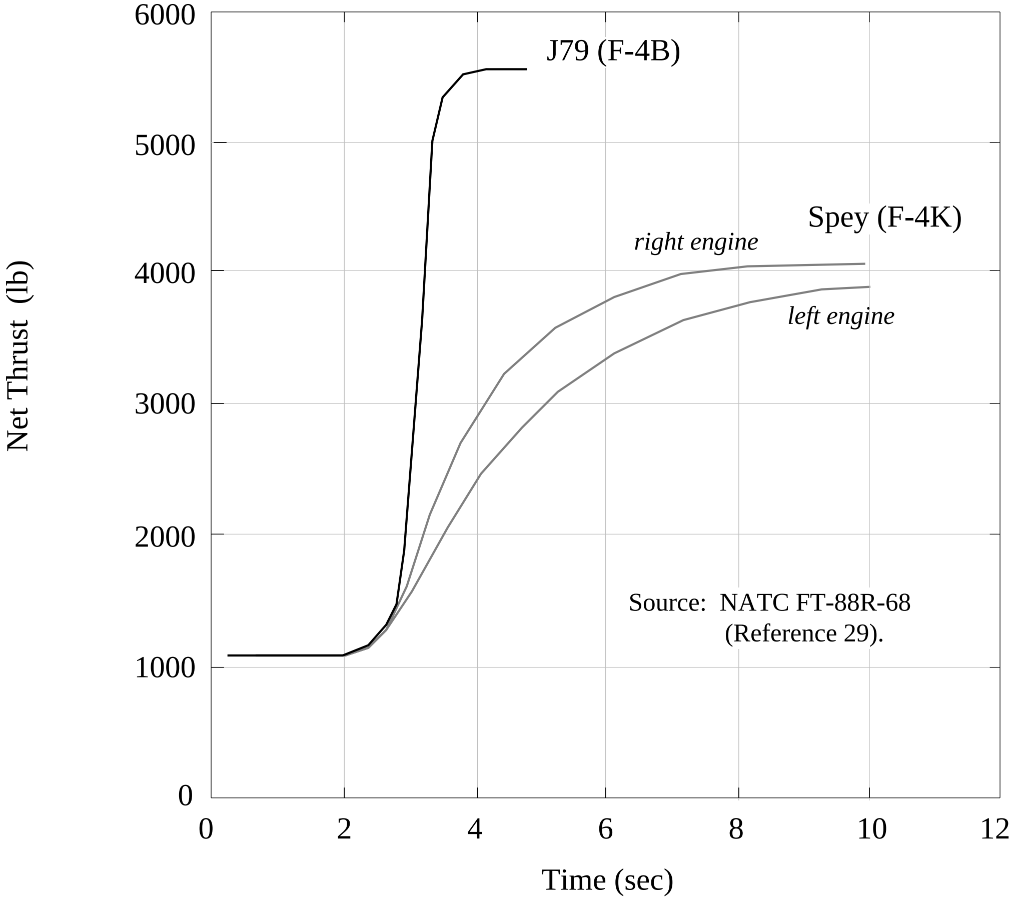


Figure 2-21. Thrust Lag Data for the F405 Engine (T-45).

Another important attribute that is not shown directly in these data is the long lag experienced when reducing thrust from nominal and subsequently increasing it. NATC made measurements using a “spooldown-reslam” test. This consisted of starting with the engine stabilized at approach power, decreasing the throttle to idle for one second, then immediately increasing it to Military power. The acceleration characteristics were about the same as indicated by the above thrust-lag plots.

Figure 2-22 shows a comparison of throttle steps for the standard J79 and Rolls Royce Spey engines installed in the F-4B and F-4K aircraft, respectively (Reference 29). The effective lags in this case are 0.1 sec for the J79 and 1.4 sec for the Spey. This also illustrates the magnitude of thrust lag difference which can be found in conventional turbojet and high-bypass turbofan engines.



Source: NATC FT-88R-68 (Reference 29).

Figure 2-22. Comparison of J79 and Spey Engines in F-4 Aircraft.

2.3 Examples of Simulated Carrier Landings (FCLP)

The Naval Air Test Center also supplied several examples of approaches made during field carrier landing practice (FCLP) in References 56-58. These data reflect several aircraft types and involve normal approaches as well as some intentional off-nominal conditions.

The plotted states, extracted from laser-tracker data and plotted below, consist of glideslope error, Δd, and error rate, $\Delta \dot{d}$, as a function of range.[22] Lineup and speed (including angle of attack) were included in the data collection but are not plotted here.

Figure 2-23 shows six A-6E approaches, 2-24 two F-14A approaches, 2-25 one F-18 approach, and 2-26 two T-45A approaches. One analysis procedure in Section 4 will illustrate how some attributes of pilot task performance can be extracted from such data. However, one should recognize that the data do not portray actual carrier approaches and do not have sufficient accompanying commentary to draw major conclusions on task performance.

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[22] There are bias errors in position (Δd and Range) because the laser tracker data origin had to be estimated.

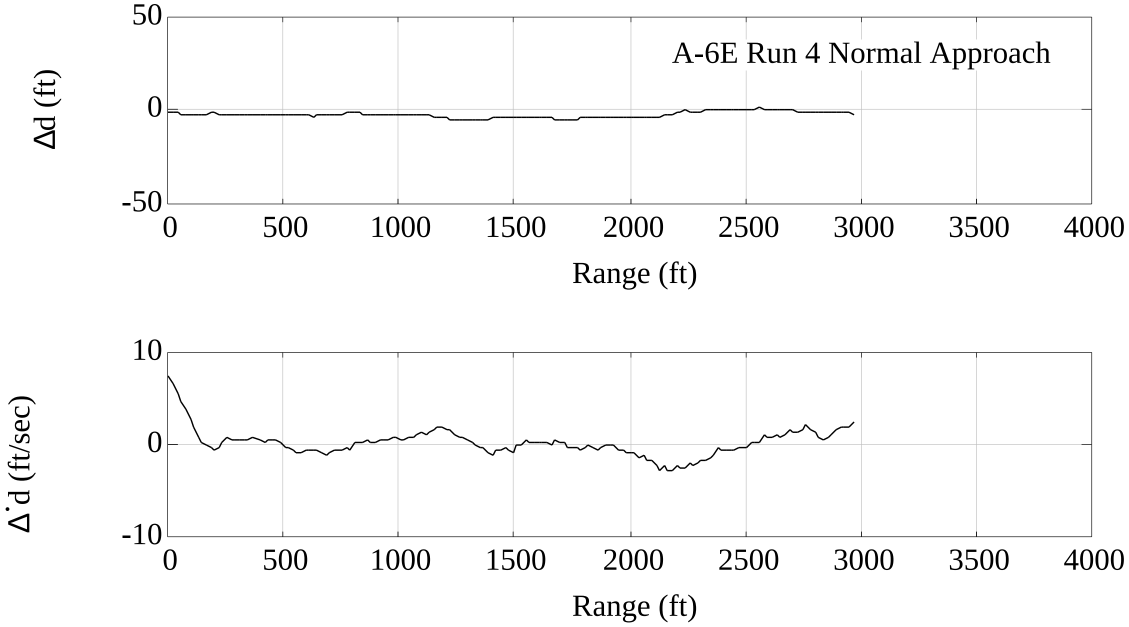

Figure 2-23a. FCLP Approach Example for A-6E.

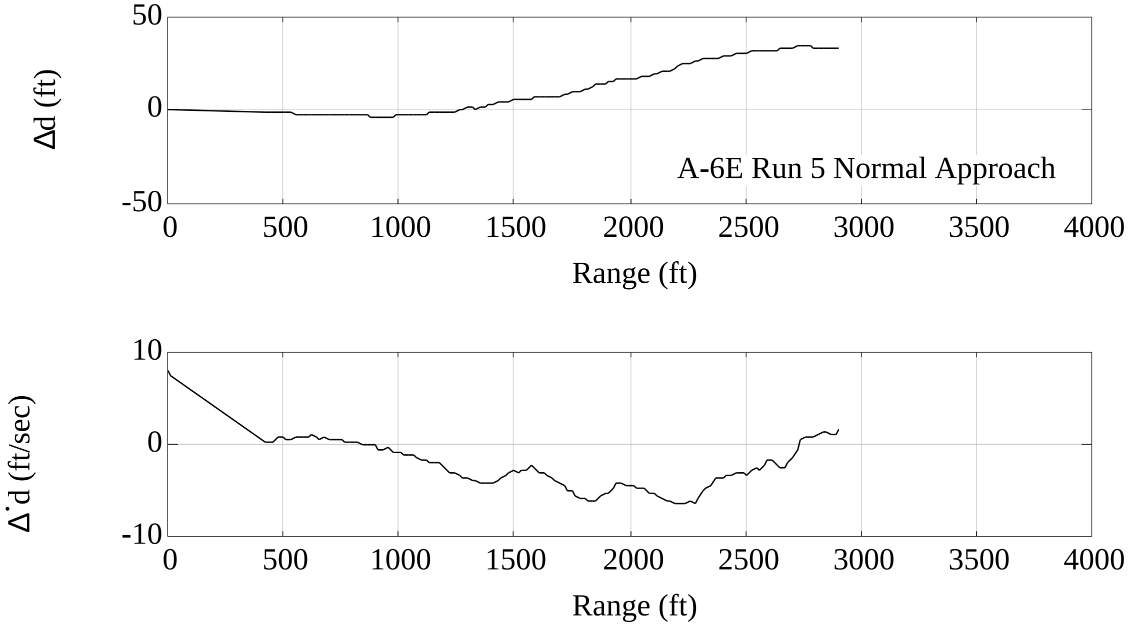

Figure 2-23b. FCLP Approach Example for A-6E.

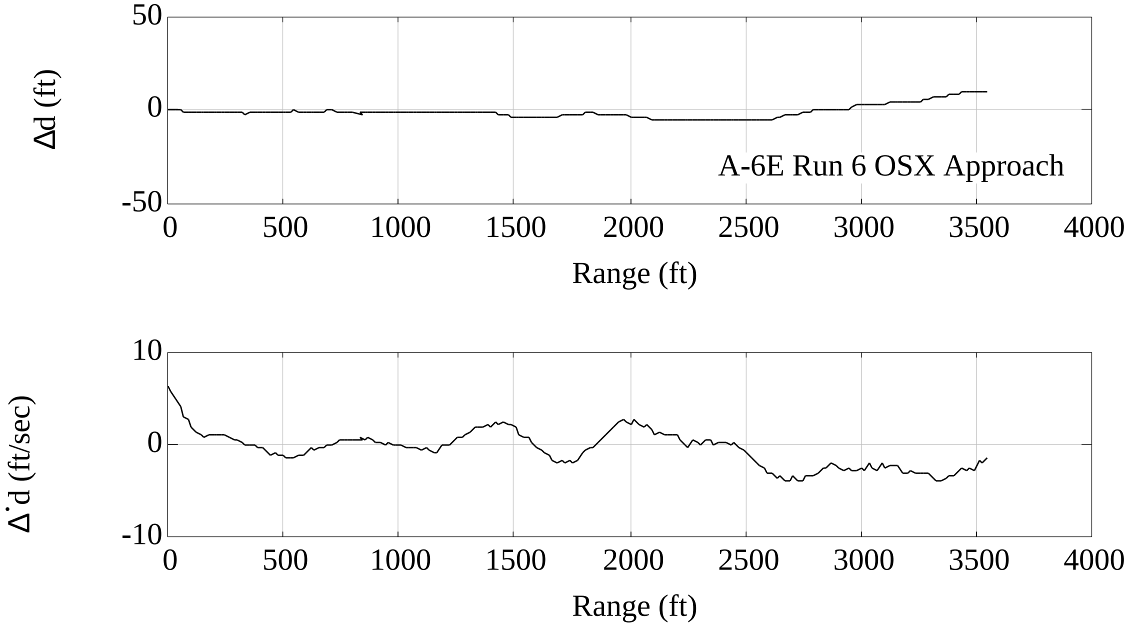

Figure 2-23c. FCLP Approach Example for A-6E.

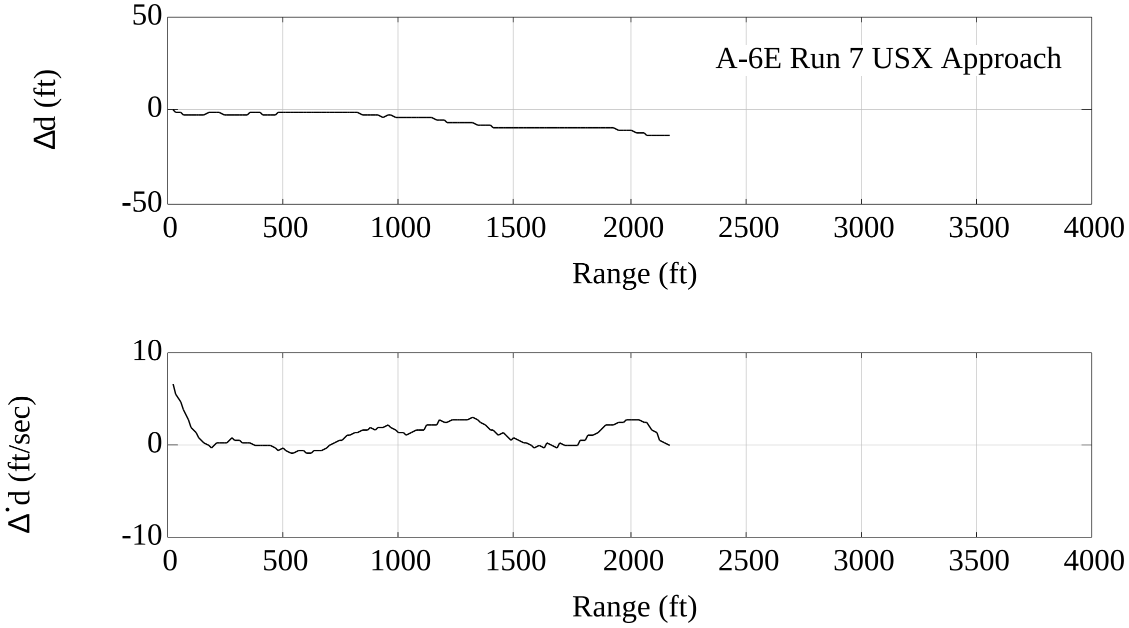

Figure 2-23d. FCLP Approach Example for A-6E.

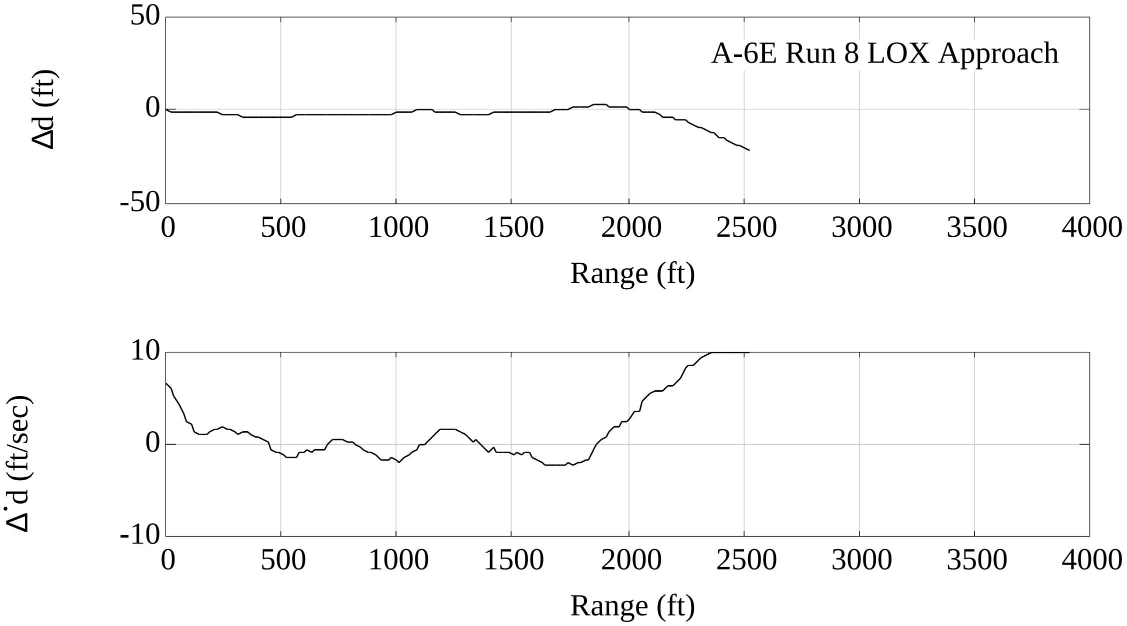

Figure 2-23e. FCLP Approach Example for A-6E.

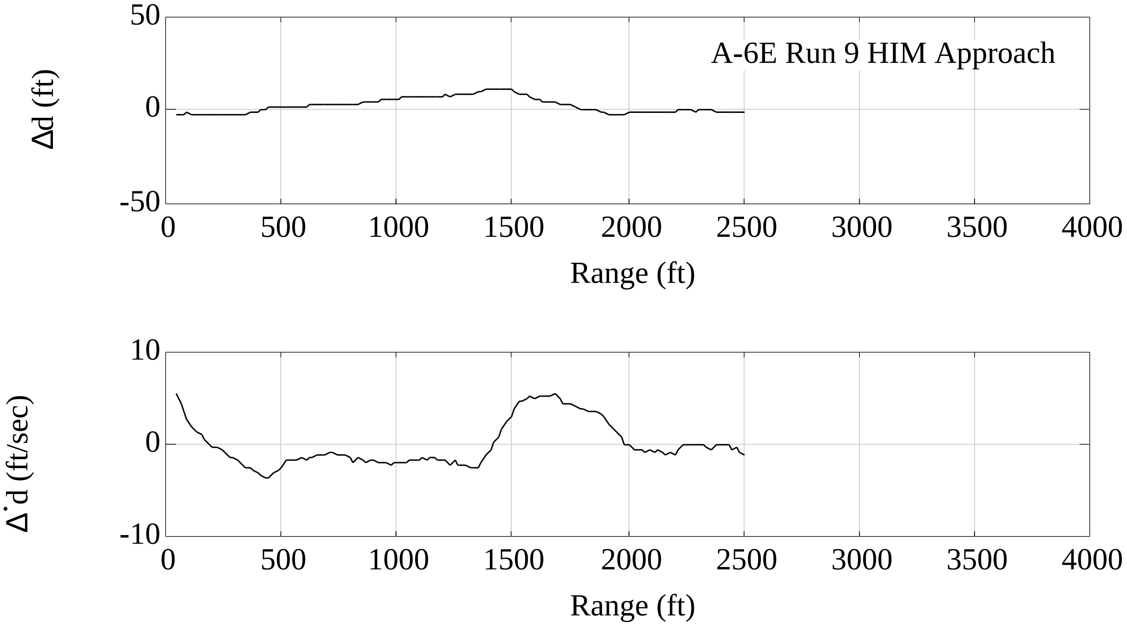

Figure 2-23f. FCLP Approach Example for A-6E.

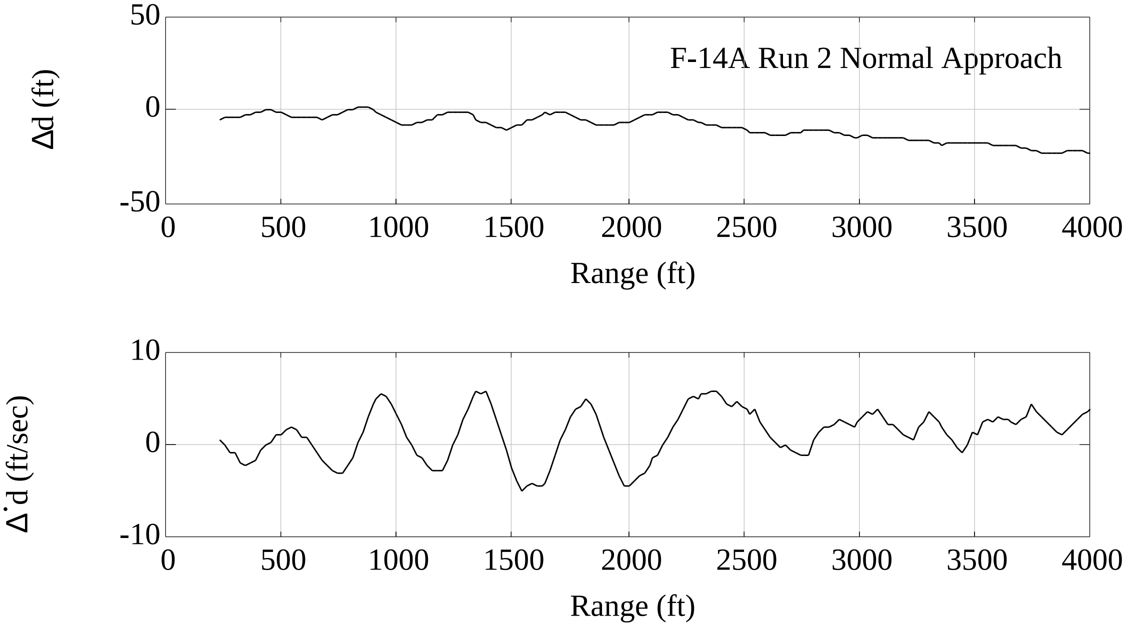

Figure 2-24a. FCLP Approach Example for F-14A.

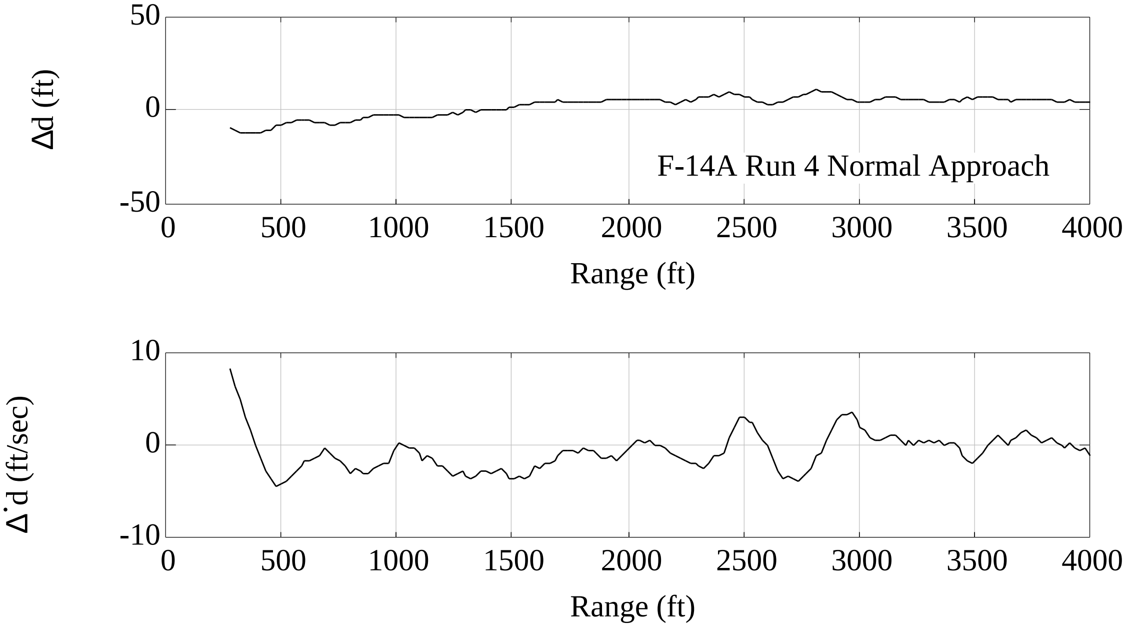

Figure 2-24b. FCLP Approach Example for F-14A.

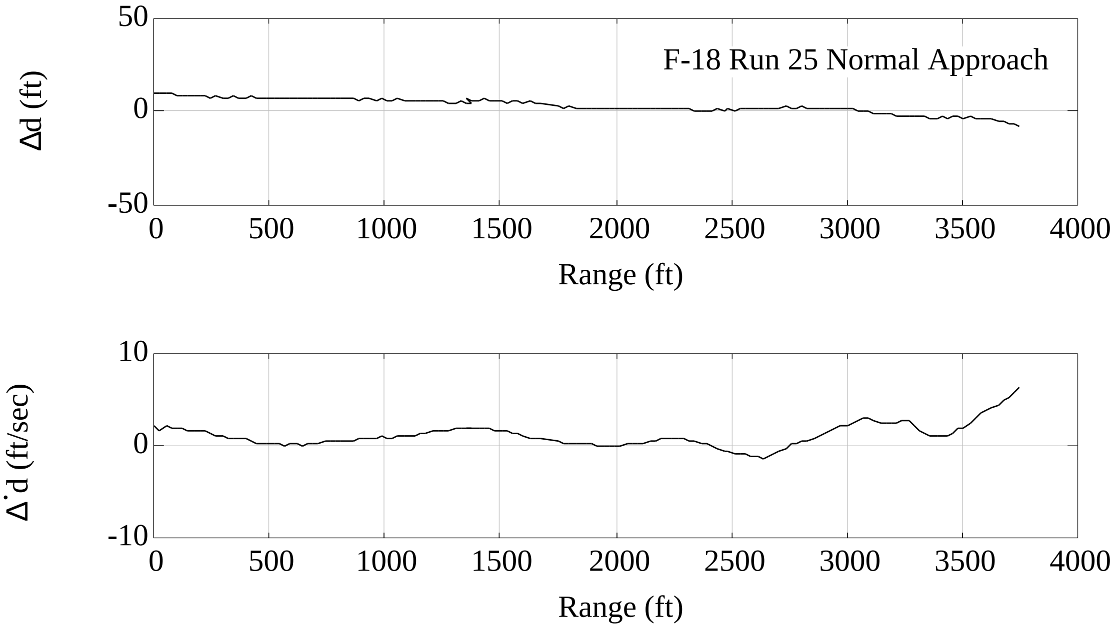

Figure 2-25. FCLP Approach Example for F-18A.

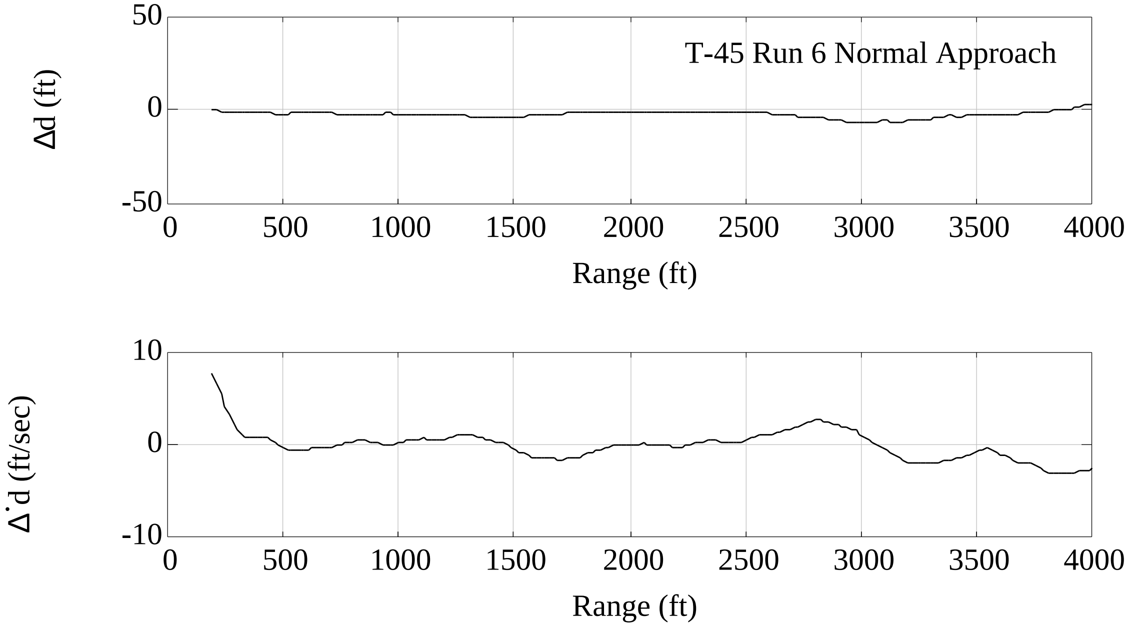

Figure 2-26a. FCLP Approach Example for T-45A.

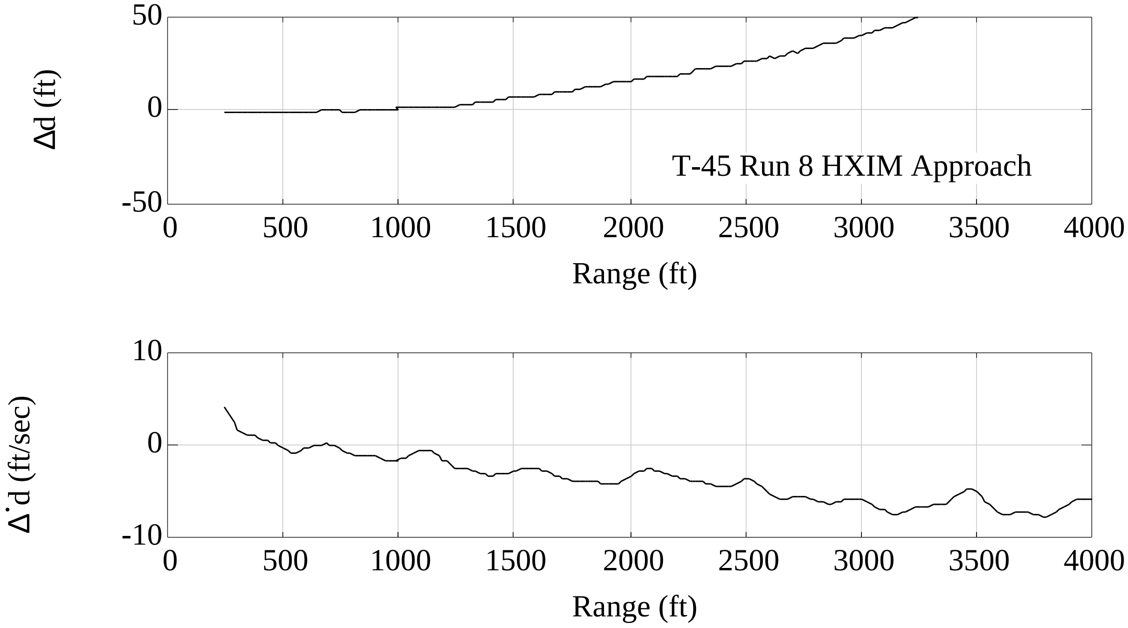

Figure 2-26b. FCLP Approach Example for T-45A.

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3. CARRIER LANDING PILOT-VEHICLE-TASK MATH MODELS

The purpose of the math modeling process is to enable a systematic examination of any or all the parts of the pilot-vehicle-task system. To do so, one must establish a valid operational context. That is, the dynamics must be viewed in the appropriate range of interest, whether in the time domain or frequency domain.

Since the focus is on the outer-loop dynamics it is possible to take advantage of several simplifying assumptions. In fact, one can view the aircraft as a low-order system in nearly all cases (first-, second-, or third-order). This makes it feasible to study the total pilot-vehicle closed loop system without incurring undue complexity.

Following the form of previous sections, the author examines the carrier landing task first, the aircraft next, and finally the total closed-loop system including the pilot.

3.1 Carrier Environment (Task)

Analytical study of the carrier landing task aids in the formulation math models in the correct context. Because the pilot receives outer-loop information primarily in the visual modality, the aircraft motion needs to be computed at the pilot's station. Simultaneously, a crucial performance-related aspect is the position of the tailhook relative to the arresting wires on the deck. Finally, one ordinarily solves the airplane equations of motion with respect to the aircraft cg. The analyst may need to distinguish each of these reference frames, depending upon the circumstances.

3.1.1 Glideslope Task

The Fresnel Lens Optical Landing System (FLOLS) is the most prominent guidance feature in the carrier landing environment. A detailed description of the FLOLS system can be found in Reference 40.

The vertical array of five Fresnel lens provides a nearly-continuous[23] display of glideslope error over the 1.6° vertical beamwidth and 40° horizontal beamwidth. Figure

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[23] Characteristics of the ball are sensitive to temperature changes in the internal Fresnel lens cell. If the lens assembly is not completely warmed-up there may not be a smooth transition of the ball between cells and the ball may disappear as it tranverses the junction between adjacent cells. Under normal operating conditions, however, the motion of the ball should be smooth and continuous.

3-1 shows key glideslope features seen by the pilot. The glideslope light assembly has five Fresnel lens cells mounted vertically. Four of the lights are yellow in color and the bottommost (the extreme-low indication) is red. Personnel aboard the carrier can vary intensity depending upon ambient light and weather conditions.

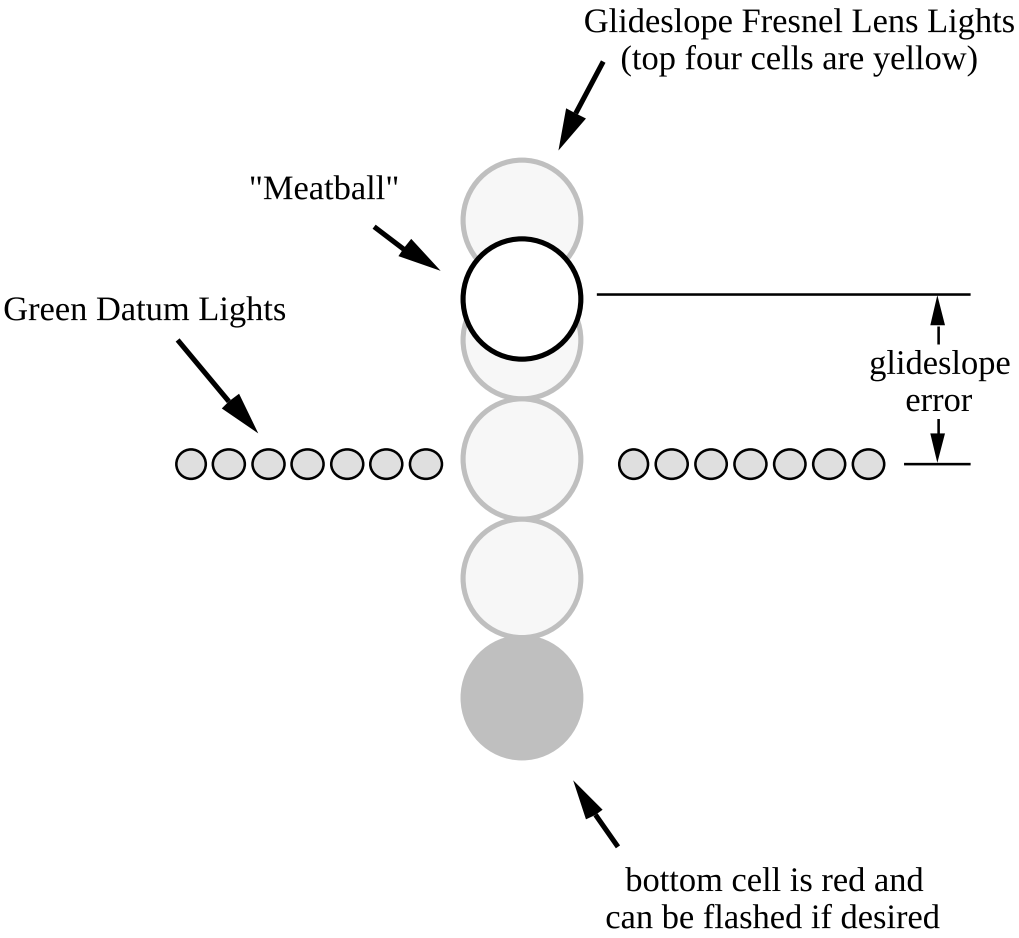

Figure 3-1. FLOLS Glideslope Display Geometry.

Three fixed datum lights and four conditional datum lights are mounted horizontally on each side of the lens. The fixed datums are illuminated continuously while the conditional datums go out when the waveoff lights are on.

Four waveoff lights and three auxiliary waveoff lights are mounted vertically on each side of the lens. When the LSO initiates a waveoff, the waveoff lights first flash at full intensity then dim to the preset brightness.

The lens assembly can be tilted about two horizontal planes at right angles to each other that equate roughly to the ship's pitch and roll axes. The tilt in pitch gives the basic glideslope angle and it seldom changes (3.5° to 4°). Moving the lens about the roll axis rolls the glideslope and causes the glideslope at the landing area to be raised or lowered as Figure 3-2 shows. This compensates for the hook-to-eye distance of various aircraft to produce a constant hook glide path for all aircraft.[24] Roll angle can be varied from 0 to 15 units. At 7.5 units all cells are vertical; 15 units cants the top of the cells outboard and provides for maximum ramp clearance, i. e., settings for the largest hook-to-eye distance. One potential problem is that for large lens-assembly roll angles, extreme off-center approaches can result in hazardous ramp clearance.

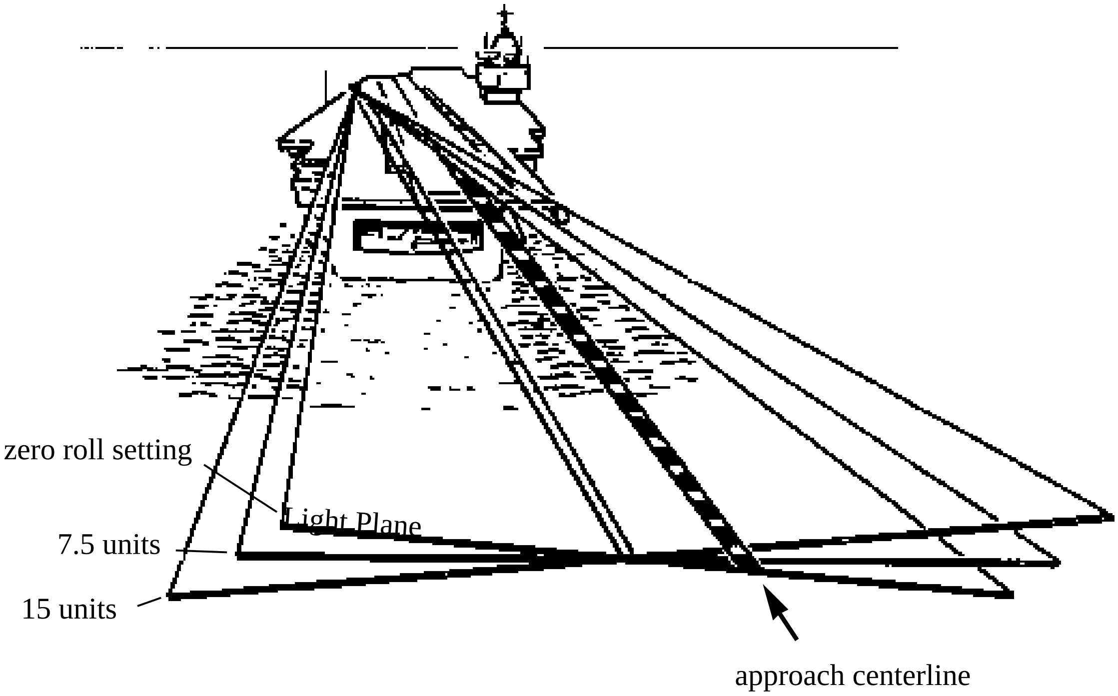

Figure 3-2. Effect of FLOLS Roll Angle on Light Plane.

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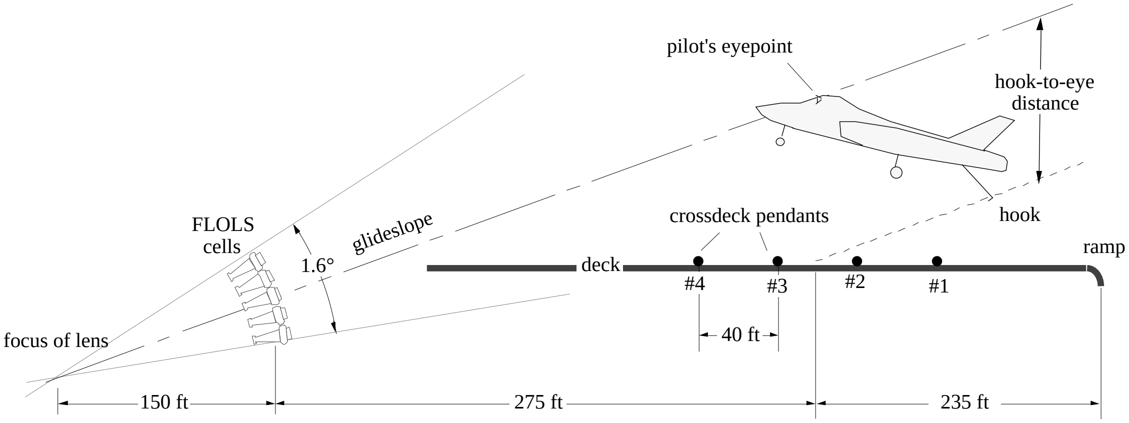
[24] See Table 2-6 for hook-to-eye distances.

Hook-to-eye values for most aircraft are such that the lens is either upright or tilted top outboard (exceeds 7.5 units).[25] Published lens settings provide optimum hook glide path, with hook touchdown halfway between number two and number three crossdeck pendants. Roll angle places the visual glideslope a distance above the hook glideslope that corresponds to each aircraft's hook-to-eye distance. The hook-to-eye is determined for each aircraft, properly configured, flying on-speed pitch with a centered meatball. Failure to maintain optimum aircraft attitude to touchdown may result in engagement of other than the target wire though the pilot sees a centered ball at touchdown.

Figure 3-3 shows a sideview of the FLOLS glideslope geometry. Note the fundamental difference in the path of the pilot's eye as compared to that the hook follows to its terminal condition on the deck.



note: dimensions approximate, not to scale, and can vary according to ship

Figure 3-3. Sideview of FLOLS Geometry.

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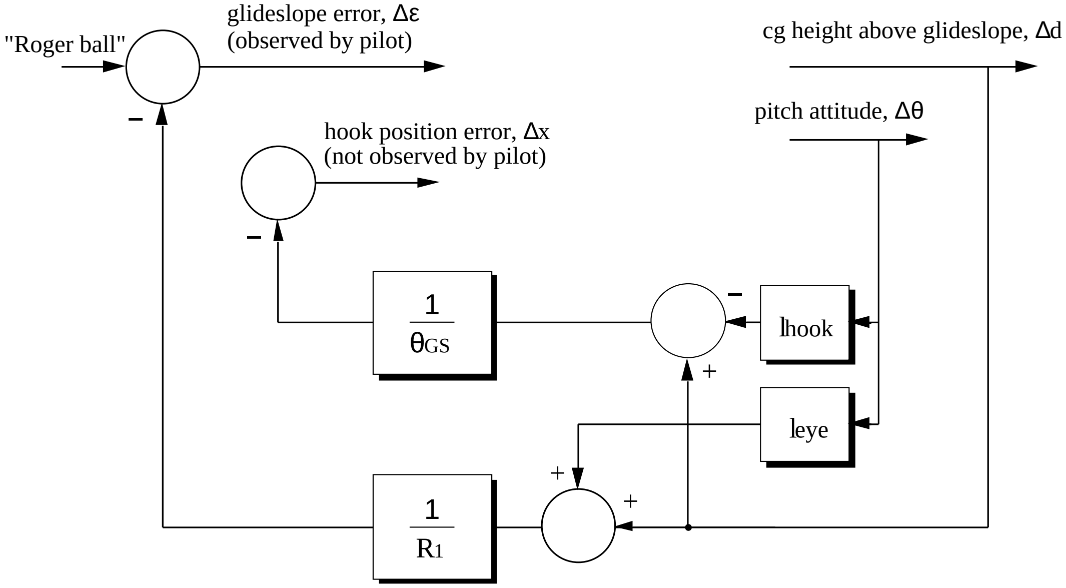
[25] An exception is the F-8 aircraft. Note that it has the smallest hook-to-eye distance in Table 2-6.

Figure 3-4 shows the math model needed to address the features of the glideslope guidance and the hook-to-eye geometry. This model emphasizes that there are two important error states, the *FLOLS glideslope error* observed by the pilot and the *hook position error* with respect to the crossdeck pendant location along the deck. The latter is unobserved by the pilot.

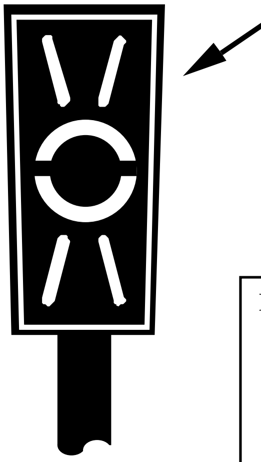


R_1 range from pilot to focus of FLOLS
= Range to touchdown + 425 ft
l_{hook} distance from cg to hook
l_{eye} distance from cg to pilot's eye
θ_{GS} glideslope angle (rad)

Figure 3-4. Math Model of Glideslope Geometry.

3.1.2 Angle-of-Attack Task

The pilot regulates approach speed using a loose loop closed around angle-of-attack. An indexer on the glareshield prominently displays AOA to the pilot. Figure 3-5 shows an example based on information from the A-6 NATOPS Manual (Reference 59).



Key to Display

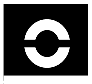
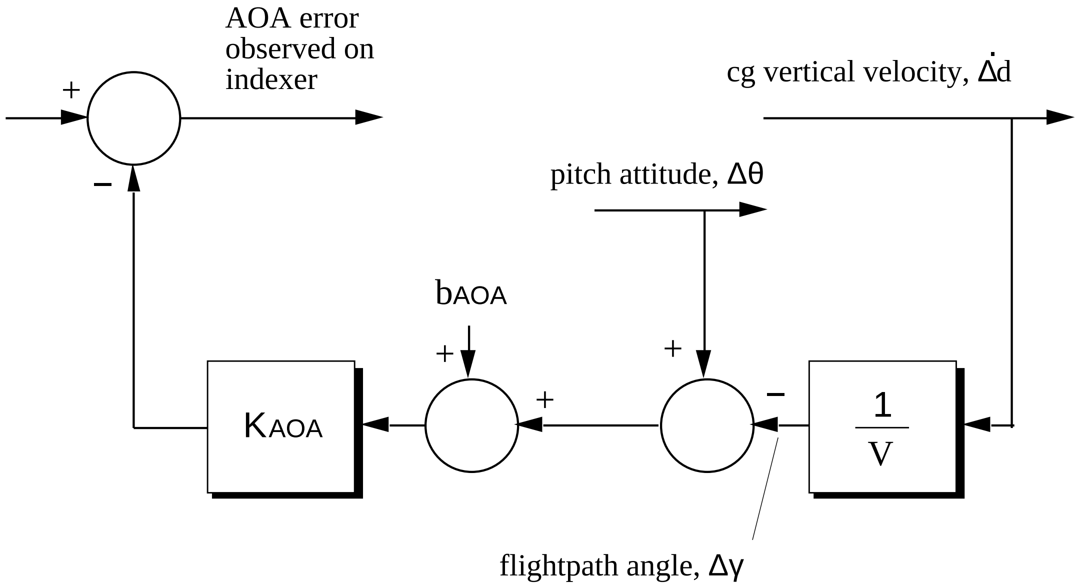
INDEXER SYMBOL	ANGLE OF ATTACK	APPROACH LIGHT COLOR (Visible to LSO)
	High α (Slow)	Green
	Slightly High α (Slightly Slow)	Amber
	Optimum α (On Speed)	Amber
	Slightly Low α (Slightly Fast	Amber
	Low α (Fast)	Red

Figure 3-5. Angle-of-Attack Indexer Display.

The angle of attack error observed by the pilot is essentially a linear function of the true α, and this is shown in Figure 3-6. It is important to note that the same aircraft state variables are involved (Δ θ and the derivative of Δ d). Figure 3-6 diagrams this only to emphasize the point. Its significance will be discussed in subsequent sections.



V true airspeed

b_{AOA} AOA system bias

K_{AOA} AOA system proportionality factor

Figure 3-6. Math Model of AOA Display.

3.1.3 Lineup Task

The pilot gets lateral flightpath information mainly through the perspective view of the landing area as in a normal field landing. The essential features shown in Figure 3-7 are the canted deck centerline, dropline, and horizon (if visible). From the pilot's viewpoint, the angle, λ, indicates the lateral offset between the deck centerline and either the horizon or the vertical dropline extending off the stern of the ship. The former would be more useful under normal daytime conditions, and the latter at night.

λ arctan(y/h)
where y is lateral offset
and h is altitude above deck.

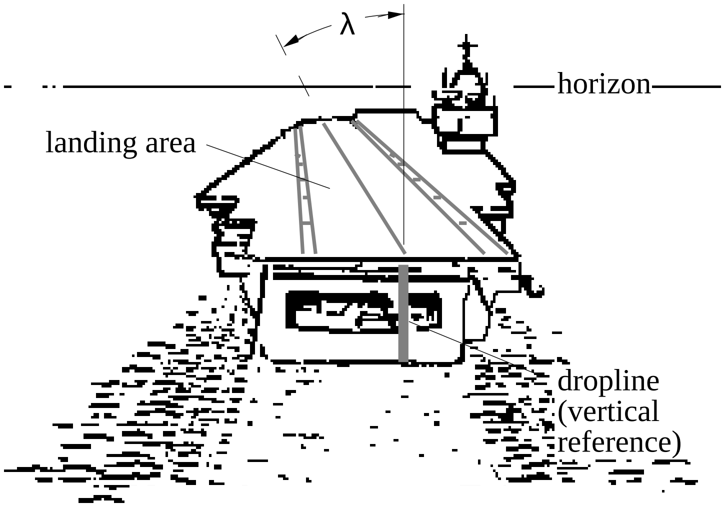


Figure 3-7. Lineup Geometry.

3.2 Aircraft and Flight Control Systems (Vehicle)

The math models used to describe the aircraft and its flight control systems typically can vary greatly both in form and complexity. The main requirement is that the dynamics of the model are correct in the spectral range of interest and appropriate to the piloting task considered.

Traditional flying qualities are concerned with characteristics represented by the higher-frequency classical response modes (short-period, Dutch-roll, and roll). Therefore, requirements address natural frequency, damping, response times, manipulator sensitivity, and manipulator feel. Other lower-frequency-regime features are also covered by flying qualities. It is correct to associate items such as phugoid and spiral with unattended operation than with closed-loop control.

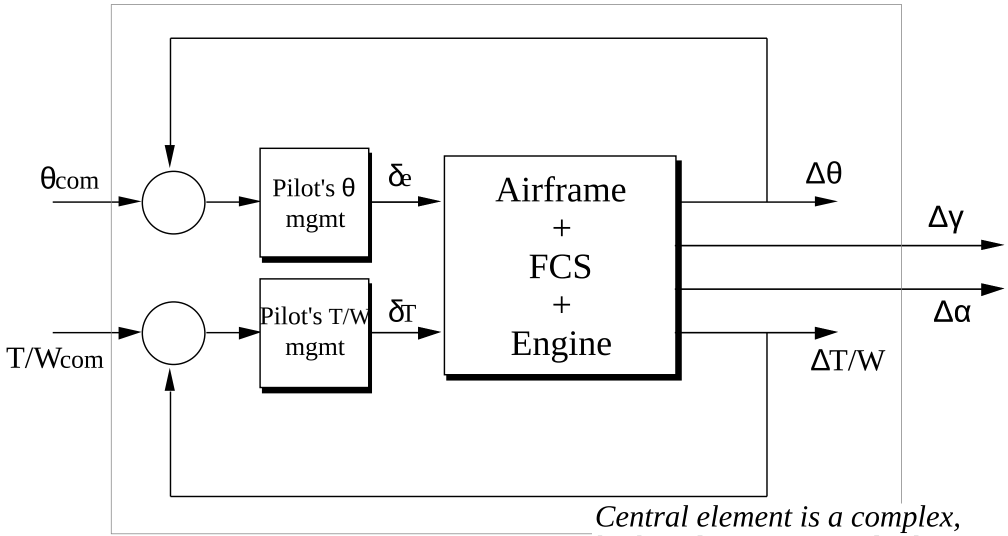
One problem with the traditional way of viewing aircraft dynamics is that when focusing on the outer-loops, the high overhead in complexity associated with inner-loop features distracts the analyst. This is true even when dealing with a basic unaugmented aircraft, and complex flight control systems compound it.

There is a great practical advantage to partitioning inner- and outer-loop features. One benefit is the analyst's understanding of the physical system. Another is that calculations are simple and checkable with reasonable effort. Finally, it is usually cheaper and faster to begin systems analysis with minimal simplicity and increase complexity as needed than it is to do the reverse. This, then, is the motivation for the technical approach introduced earlier in Section 1, namely, the use of pitch-constrained equations of motion.

3.2.1 Pitch-Constrained Equations of Motion

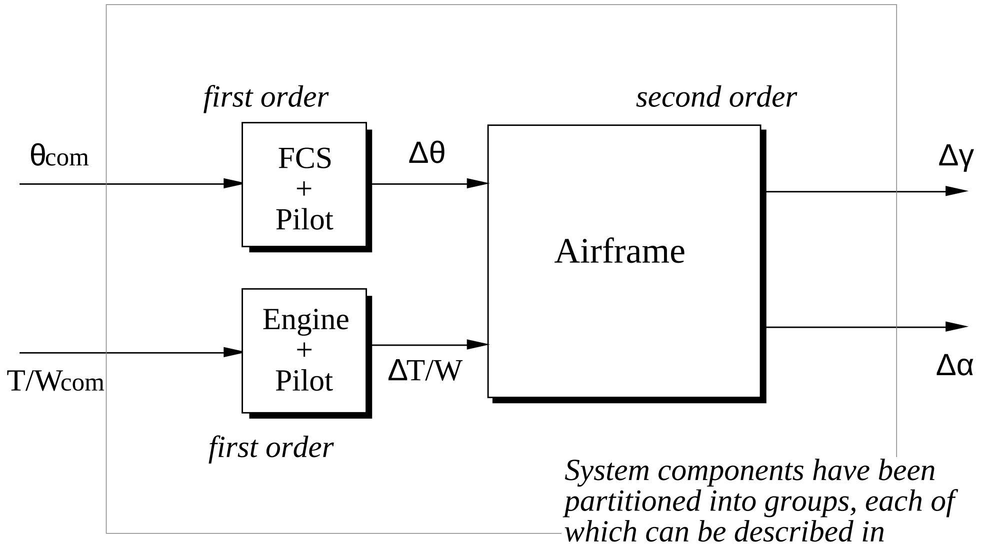
The system analyst realizes considerable benefit by assuming the pilot is actively managing attitude. For examination of outer-loop features, one can rearrange the system architecture as Figure 3-8 illustrates. The traditional architecture must lump airframe, engine, and flight control system into a complex, high-order system and include the pilot's regulation of the inner control loops around pitch attitude and, possibly, thrust (Figure 3-8a.). On the other hand, by the implicit assumption of good inner-loop regulation, the three major components (airframe, engine, and FCS) can be separated and each modeled as low-order systems (Figure 3-8b). Another major benefit is the removal of explicit inner-loop feedback paths.

a. Traditional Pilot-Vehicle System Architecture:



Central element is a complex, high-order system, and pilot inner control loop add even more complexity.

b. Pitch-Attitude-Constrained System Architecture:



System components have been partitioned into groups, each of which can be described in simple, low-order terms.

Figure 3-8. Comparison of Pilot-Vehicle Architectures.

The airframe component needs to be described only by “trimmed” lift and drag data. The FCS and engine blocks each can be represented by an effective lag or by the closed-loop pilot-engine or pilot-FCS bandwidth,[26] whichever is considered more appropriate. Because of the spectral separation of engine and FCS from flightpath and speed, the specific details of the engine and FCS blocks are generally not so influential as the airframe lift and drag. Therefore the main outer-loop system factors can be summarized by the simple second-order system description given in Table 3-1.

The factors that comprise the Laplace-transform denominator and numerators listed above are easy to compute. The data required are few and estimates are not difficult should some data not be available. Table 3-2 gives a list of approximate factors. Approximate-factors relationships are useful for describing the primary audit trail between aircraft design features and control characteristics. Some approximate factors are fairly accurate and imply ways for selecting specification parameters and criteria.

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[26] This refers to the effective aggressiveness that the pilot exhibits when actively regulating pitch or thrust. Normally it is sufficient to assume a simple first-order lag which is matched to the level of aggressiveness.

Table 3-1. Outer-Loop Airframe System Dynamics.

Equations of Motion:

$$\begin{bmatrix} (s - Z_w) & Z_u \\ X_w & (s - X_u) \end{bmatrix} \begin{bmatrix} \Delta \dot{d} \\ \Delta u \end{bmatrix} = \begin{bmatrix} -Z_\alpha & \eta \, g \\ (X_\alpha - g) & g \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta T/W \end{bmatrix} \qquad (1)$$

where:

$$\Delta w/V = \Delta \alpha = \Delta\theta - \Delta\gamma \quad \text{, and} \qquad (2)$$

$$\Delta \dot{d}/V = \Delta \gamma \qquad (3)$$

Outer-Loop Denominator:

$$\Delta = (s - Z_w)(s - X_u) - X_w Z_u = (s + 1/T_{\theta 1})(s + 1/T_{\theta 2}) \qquad (4)$$

Outer-Loop Numerators:

$$N^{\gamma}_{\theta} = -Z_w [s - X_u + Z_u(X_\alpha - g)/Z_\alpha] = g/V \cdot n_{z\alpha} (s + 1/T_{h1}) \qquad (5)$$

$$N^{\gamma}_{T/W} = g/V(-Z_u - X_u \eta + \eta s) = 2(g/V)^2 \cdot (1 + T_{h\theta} s) \qquad (6)$$

$$N^{\alpha}_{\theta} = \Delta - N^{\gamma}_{\theta} = s^2 - X_u s - Z_u g/V \approx [s^2 + \omega_p{}^2] \qquad (7)$$

$$N^{\alpha}_{T/W} = -N^{\gamma}_{T/W} \qquad (8)$$

$$N^{u}_{\theta} = (X_\alpha - g)[s - Z_w + Z_\alpha X_w/(X_\alpha - g)] = -g \, n_{x\alpha}(s + 1/T_{u1}) \qquad (9)$$

$$N^{u}_{T/W} = g(s - Z_w - \eta X_w) = g(s + 1/T_{u\theta}) \qquad (10)$$

Table 3-2. Outer-Loop Approximate Factors.

$$X_u = -\rho VSC_D / m = -2g / V \cdot C_D / C_L \tag{11}$$

$$X_w = \rho SV(C_L - C_{D\alpha}) / 2m = g / V \cdot (1 - C_{D\alpha} / C_L) = g / V \cdot (1 - n_{x\alpha}) \tag{12}$$

$$Z_u = -\rho VSC_L / m = -2g / V \tag{13}$$

$$Z_w^{\dagger} = -\rho VS\,(C_{L\alpha} + C_D) / 2m \quad \text{(where } Z_w^{\dagger}, Z_\alpha^{\dagger}, n_{z\alpha} \text{ based on trim } C_{L\alpha}\text{)} \tag{14}$$

$$Z_\alpha^{\dagger} = V \cdot Z_w = -g\, n_{z\alpha} \tag{15}$$

$$X_\alpha - g = -g\, n_{x\alpha} \tag{16}$$

$$Z_{TW} = -\eta\, g \tag{17}$$

$$X_{TW} = g \tag{18}$$

$$n_{z\alpha} = (C_{L\alpha} + C_D) / C_L \approx C_{L\alpha} / C_L \tag{19}$$

$$n_{x\alpha} = C_{D\alpha} / C_L \approx 2C_{L\alpha} / (\pi \cdot AR \cdot e) \quad \text{(for a parabolic drag polar)} \tag{20}$$

$$1 / T_{\theta 2} = g / V\,(n_{z\alpha}^2 - 1) / n_{z\alpha} \approx g / V\, n_{z\alpha} \tag{21}$$

$$1 / T_{\theta 1} = g / V \cdot 2 / n_{z\alpha} + 1 / T_{h1} = g / V \cdot 2 / n_{z\alpha} - g \cdot \partial\gamma / \partial V \tag{22}$$

$$1 / T_{h_1} = -g \cdot \partial\gamma / \partial V \tag{23}$$

$$T_{h\theta} = \eta/2 \cdot V/g \tag{24}$$

Qualitative Parameter Dependencies

Figure 3-9 shows the dependence of basic airframe parameters on some of the above outer-loop control features. Aerodynamic parameters appear in an intermediate role. This is a qualitative view of how several key design and operational factors influence aerodynamics, and in turn, flightpath and AOA response. But, this is only a piece of a larger picture.

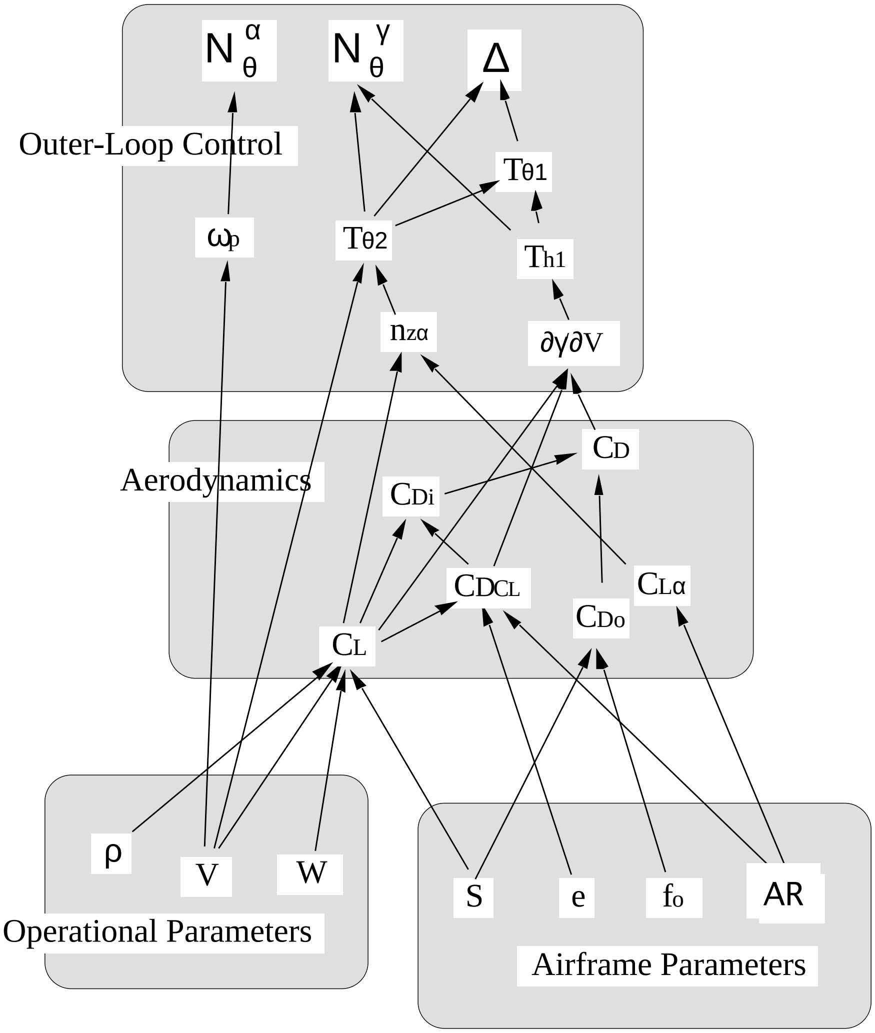


Figure 3-9. Dependence of Some Outer-Loop Features on Airframe Parameters.

One can construct a similar, more complete diagram to track other features such as the thrust response numerators, speed margin, trim attitude, and other approach-speed criteria. Figure 3-10 presents this view. Note the added role of engine parameters.

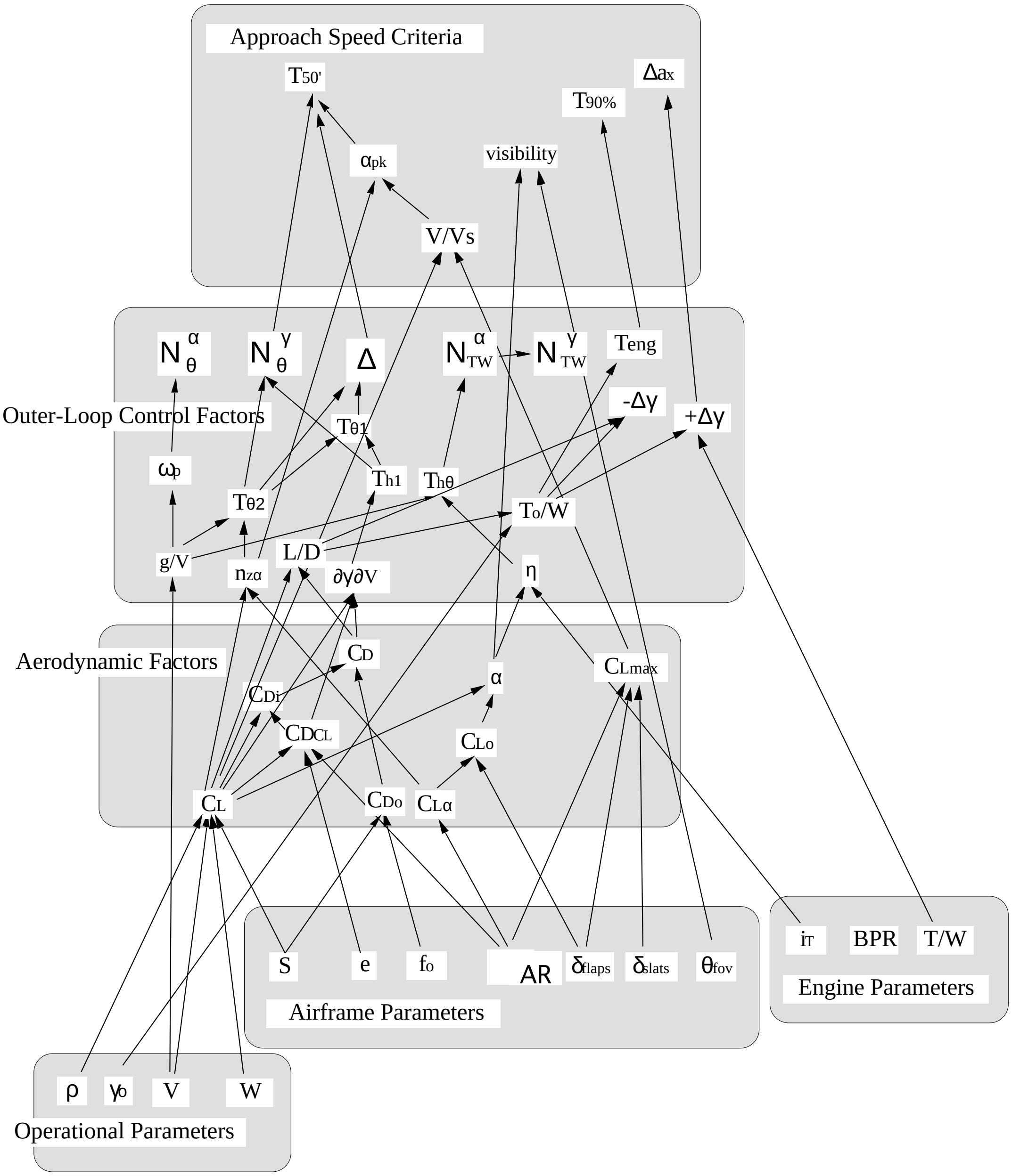


Figure 3-10. Dependence of Approach Speed Criteria on Airframe and Engine Parameters.

3.2.2 Outer-Loop Response Characteristics

The goodness of the reduced-order math model can be observed in the following series of plots. This is done for a set of typical response characteristics and can be easily repeated for any specific aircraft. The numerical values assumed are:

T_{θ_2} = 2 sec
T_{θ_1} = 10 sec
$1 / T_{h_1}$ = 0 (neutral backside)

The purpose of this section is to illustrate the general effect of various aircraft features to justify the modeling assumptions made above. This begins with higher-order features included then progressively dropped.

High-Order Model, Including Pitch Dynamics

First, consider the case for which there is no pitch-constrained assumption, that is, inclusion of all higher-order dynamics. Figure 3-11 shows the pitch attitude, flightpath, and angle of attack responses for a tight inner-loop regulation of pitch (damping ratio 0.7 and closed-loop natural frequency of 3 rad/sec). The step command of pitch attitude has a small overshoot but quickly settles to the commanded value (unity). There is evidence of the initial downward motion of the cg, followed by a short-term rise, then eventual bleedoff with loss of airspeed.

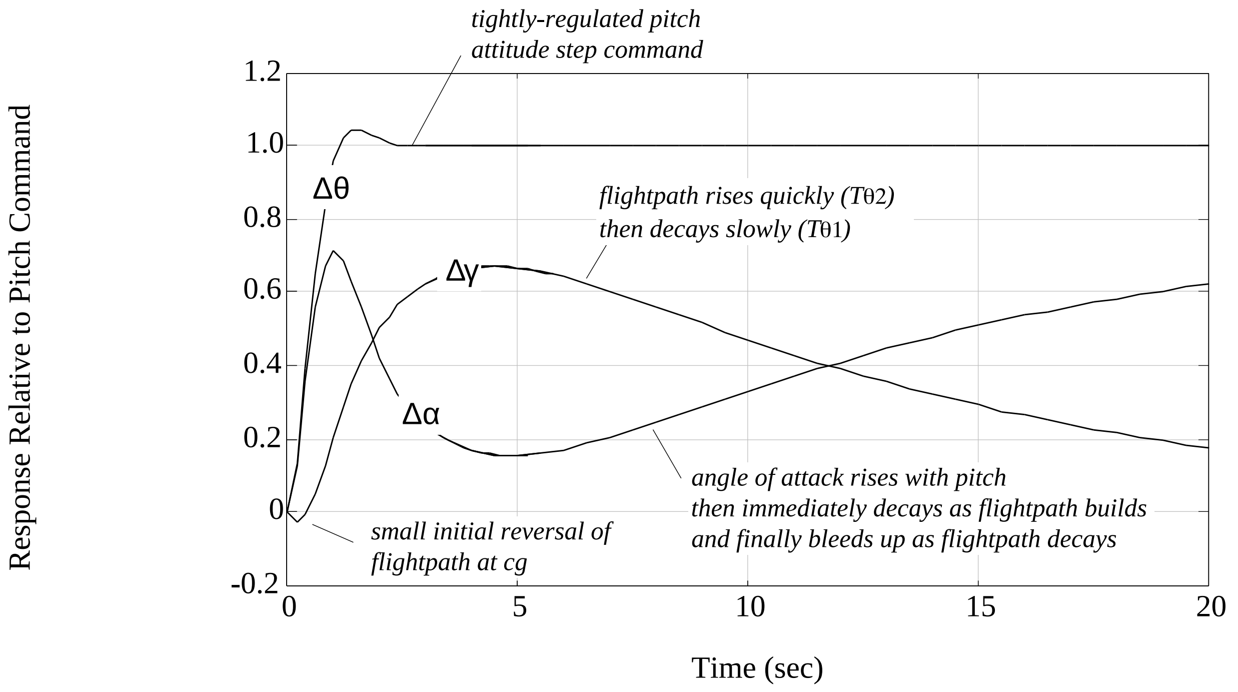


Figure 3-11. High-Order System Response to a Pitch Step.

Pitch-Attitude-Constrained Model

The next plot shows the same information, but the reduced-order dynamics are used with a simple first-order lag for the commanded pitch response. Except the very short-term response, the flightpath and angle-of-attack responses are the same. The salient features of flightpath lag and eventual bleedoff are identical with the earlier case.

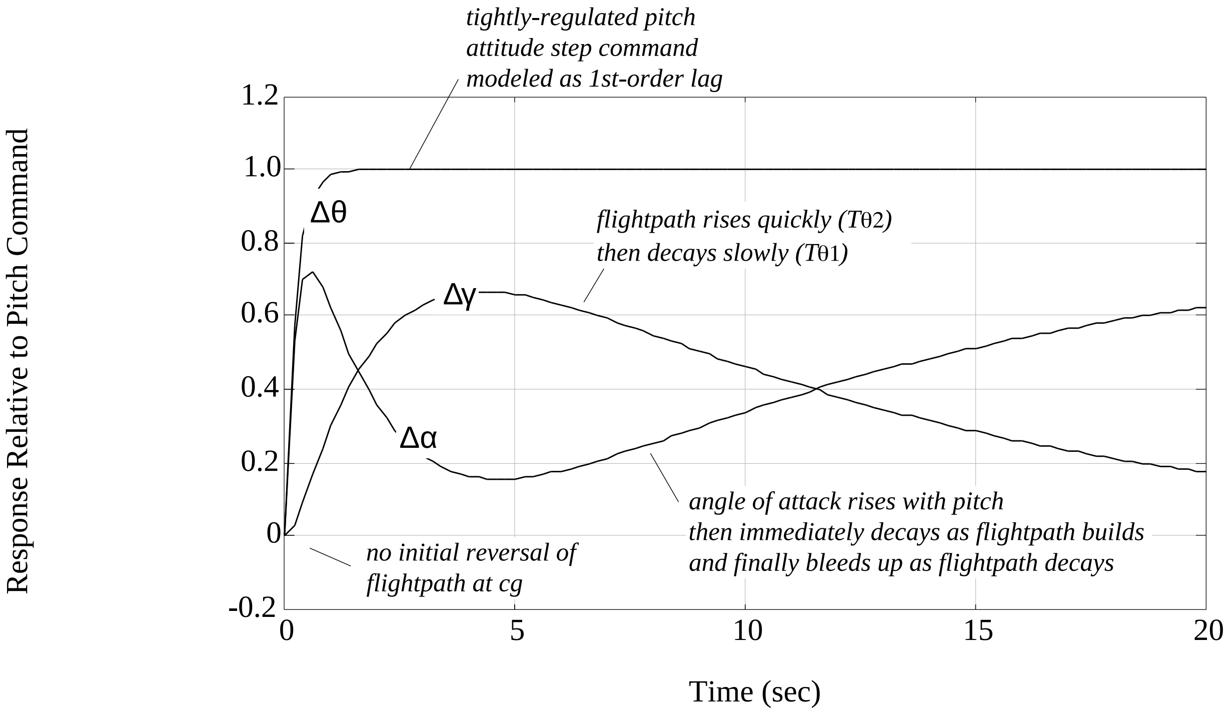
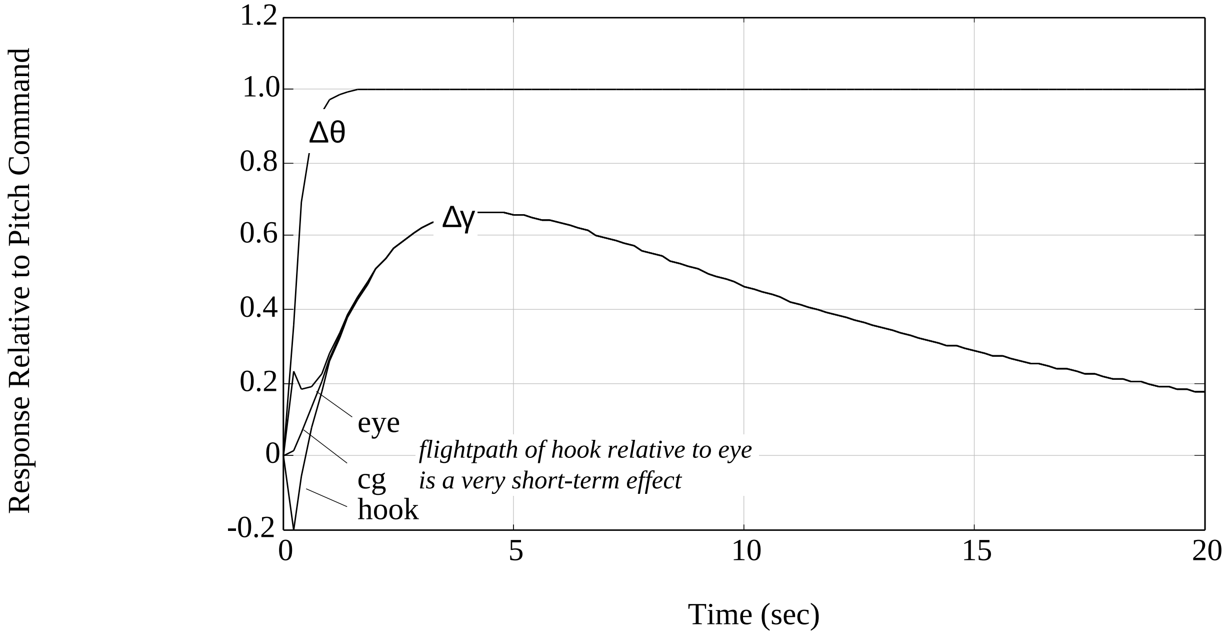


Figure 3-12. Reduced-Order System Response to a Pitch Step.

Hook-to-Eye Separation

Now consider how flightpath response varies between the pilot's eye position and the tailhook. Figure 3-13 shows three flightpath angle plots corresponding to longitudinal distance separations of 20' with an airspeed of 120 kt. The eye position is 20' ahead of the cg and the tailhook is 20' behind the cg.



flightpath of hook relative to eye is a very short-term effect

Figure 3-13. Longitudinal Position Effect on Flightpath.

Short-Term Flightpath Response

Next, using a shorter time scale, Figure 3-14 shows the theoretical relationship between pitch attitude and flightpath angle. This assumes that speed is maintained with thrust (and that angle of attack, in the long term, is held constant). Note that $T_{\theta 2}$ represents the effective lag time constant. The essential parameters are simply true airspeed, lift-curve-slope, and lift coefficient. These can be expressed in several ways and in terms of several other conventional parameters.

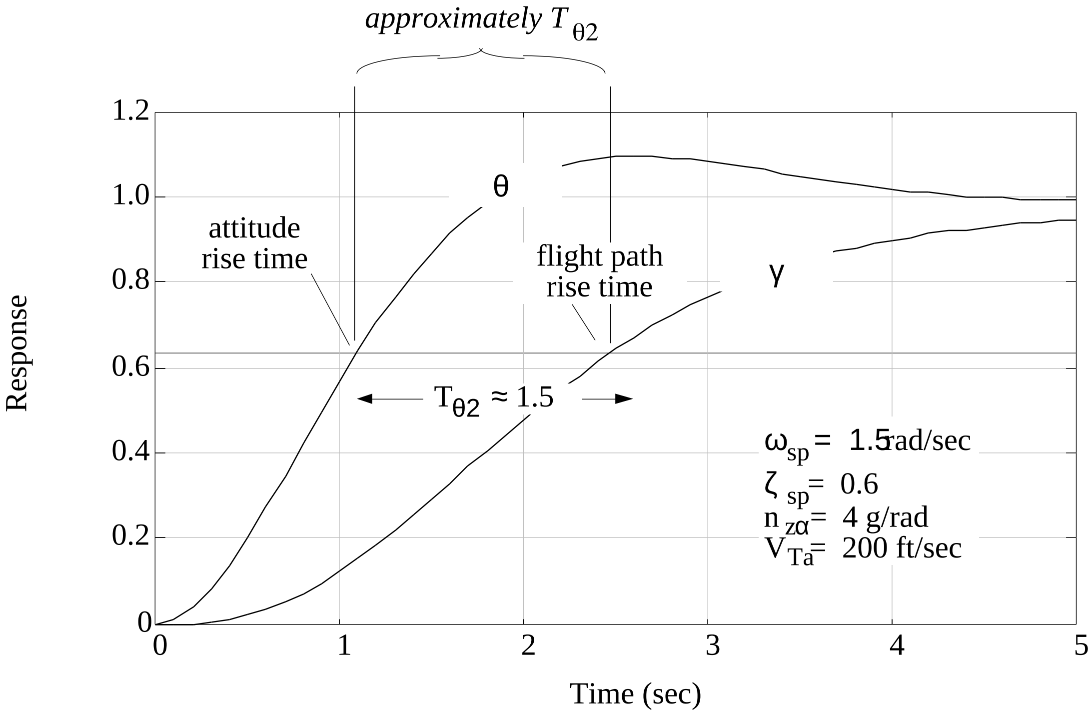
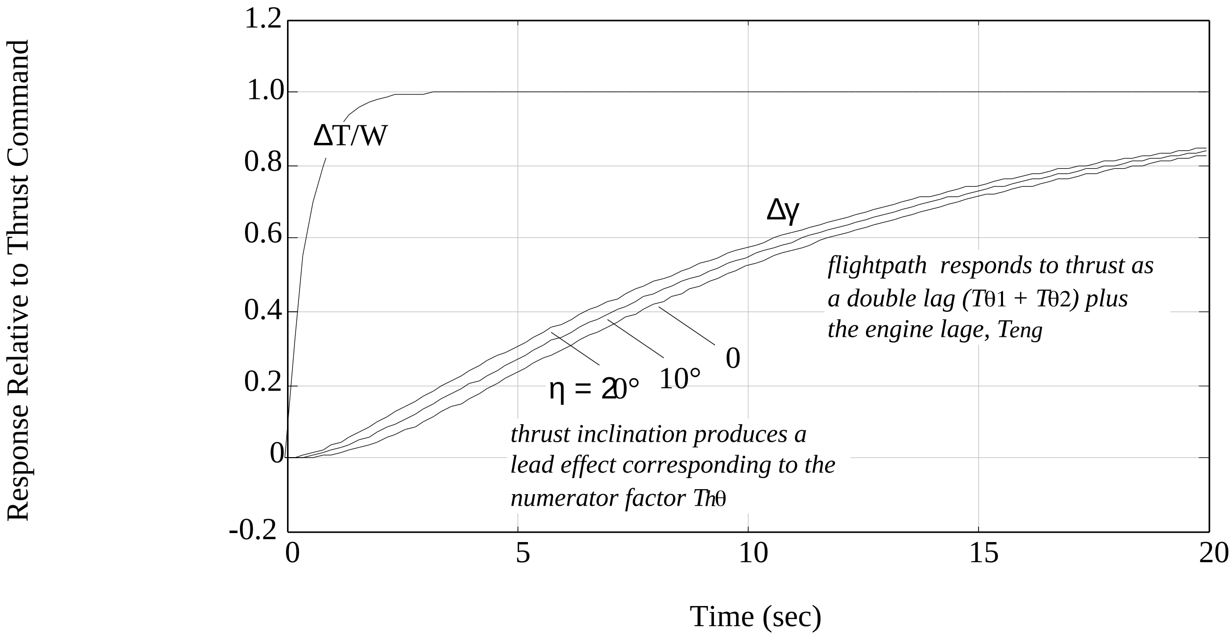


Figure 3-14. Relationship Between Pitch Attitude and Flightpath Angle.

Flightpath Response to Thrust

Inspection of the flightpath-to-thrust transfer function shows that the dominant response modes are both $1/T_{\theta 1}$ and $1/T_{\theta 2}$ (a double lag). Engine lag also adds to this. Thrust inclination angle relative to the velocity vector, η, produces a lead effect that can counter the thrust lag. Ten degrees thrust inclination produces about 0.5 sec lead if the approach speed is about 120 kt.



flightpath responds to thrust as a double lag ($T_{\theta 1}$ + $T_{\theta 2}$) plus the engine lage, T_{eng}

thrust inclination produces a lead effect corresponding to the numerator factor $T_{h\theta}$

Figure 3-15. Flightpath Response to Thrust.

3.3 Pilot and Task Control Strategy (Pilot)

The pilot and task control strategy models are the key elements that lead to identifying the design factors which govern successful task execution. In their absence only an open-loop approach can be taken.

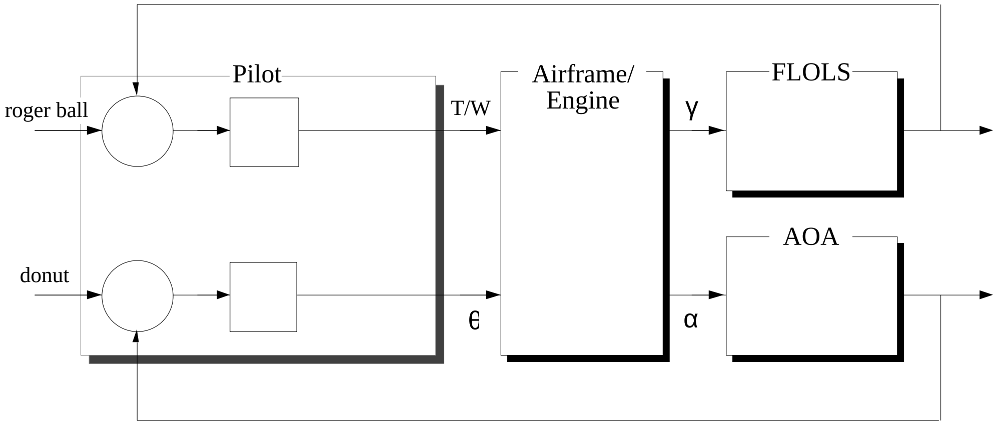
Several important analytical results relate to the effectiveness of competing pilot control strategies. The pilot control strategy as interpreted in engineering terms is crucial to the efficient extraction of performance from the airframe/engine combination. It is at least as important as the dynamics of the aircraft itself.

Outer-loop control strategy is not easily identified. Further, strategy as viewed in engineering terms, seems sometimes difficult to correlate with pilot-centered descriptions. Some more successful results have been obtained for discrete maneuvers such as the landing flare (References 60 and 61) or helicopter accel/decel maneuvers (Reference 62). In general, simpler analysis techniques seem to work as well or sometimes better than more sophisticated ones. Reference 63 contains some lessons learned in this regard.

Control strategy can be defined in terms of the incremental pitch attitude and thrust made in proportion to the glideslope and angle-of-attack errors seen by the pilot. Further, this strategy can have levels of sophistication ranging from a simple one-control-per-state to optimal blending of controls that tend to decouple the response. Figure 3-16 diagrams the two primary general levels of control strategy, *compensatory* and *pursuit,* as they are applied in this report.

The first and most profound feature of pilot control strategy or technique is its classification as either *compensatory* or *pursuit* (coordinated use of outer-loop controls). There is a fundamental difference in the structure of each, in the efficiency and ease of manual control, and in the nature of division-of-attention of the pilot.

"COMPENSATORY" MODE OF CONTROL



"PURSUIT" MODE OF CONTROL

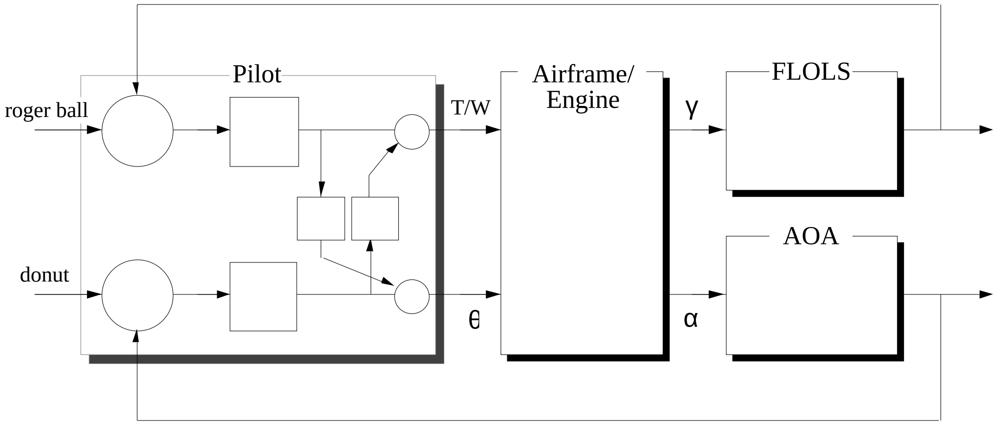


Figure 3-16. The Two Main Control Strategy Structures.

A *compensatory level* of control is the most elementary strategy and has a single control for each control variable. The case shown above is the *backside* case, i. e., thrust used to control glideslope and pitch attitude used to control angle of attack. Many consider this as the standard technique employed by navy pilots. It works even at speeds far on the backside of the thrust-required curve, but it does have serious performance limitations which shall be discussed.

Another version of the compensatory-level of control is the converse, or the *frontside* technique. Pitch attitude is the glideslope control and thrust the angle of attack control.

The choice between *frontside* and *backside* techniques is not necessarily tied to whether the aircraft is operating under the corresponding drag condition as values of either $\partial \gamma / \partial V$ or $1/T_{h1}$ indicate.

The *pursuit level* includes crossfeed paths for the two controls which result in decoupling of responses. The technique is really just a coordination or blending of thrust and pitch attitude controls. For the investment in skill development, the benefit to the pilot is enhancement of performance, especially for glideslope control, and diminished upset to angle of attack when making a glideslope adjustment.

Each above case is described in detail below.

3.3.1 Compensatory Backside Strategy (Thrust for Control of Flightpath)

The compensatory backside technique control law consists of making a thrust adjustment proportional to a flightpath or glideslope error, and a pitch attitude adjustment proportional to a speed or angle of attack error. The benefit of this technique is that it is simple and it will always work, even when speeds are well on the frontside. The disadvantage is that the quickness of the closed-loop response is greatly limited, especially for a carrier landing. The potential for a highly aggressive last second glideslope adjustment is much inferior to competing strategies.

One clear way to analyze the backside technique is to consider the response of flightpath to thrust with the angle of attack loop closed around pitch attitude. The effectiveness of the strategy can be judged by the quality of $\Delta \gamma$ response to a step $\Delta T/W$. Figure 3-17 shows the block diagram of this scheme.

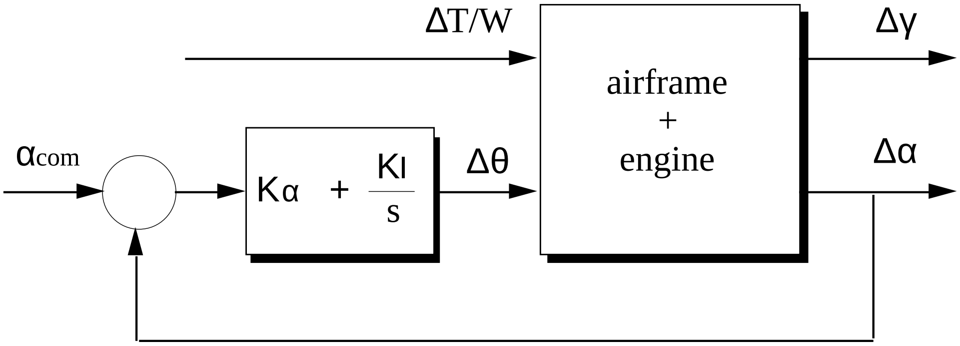


Figure 3-17. Diagram of Backside Technique.

The main factor in the backside technique is the limitation imposed in the angle-of-attack loop. Namely, as the pilot regulates α more and more aggressively, the dominant closed-loop response (starting at $1/T_{\theta 1}$ and $1/T_{\theta 2}$) migrates to the phugoid and therefore becomes a lightly-damped second-order response.

To obtain a good closed-loop response shape, the feedback must be an integral-plus-proportional blend, i. e.,

$$\Delta\theta = K_\alpha \cdot \Delta\alpha + K_I \cdot \int \Delta\alpha \, dt$$

The relative proportions of K_I and K_α need to be set about equal to the phugoid frequency in order to shape the closed-loop frequency response correctly:

$$K_I / K_\alpha \approx \omega_p$$

Figure 3-18 shows a survey of the closed-loop response. The first two plots show flightpath and angle of attack, respectively, for a step in thrust with the angle-of-attack loop closed (according to the above block diagram). Note that flightpath response requires 10 to 15 seconds during which time the angle of attack starts to bleed down. Only aggressive angle-of-attack regulation minimizes this, but the level of aggressiveness is limited to a crossover frequency less than the phugoid frequency (about 0.2 rad/sec).

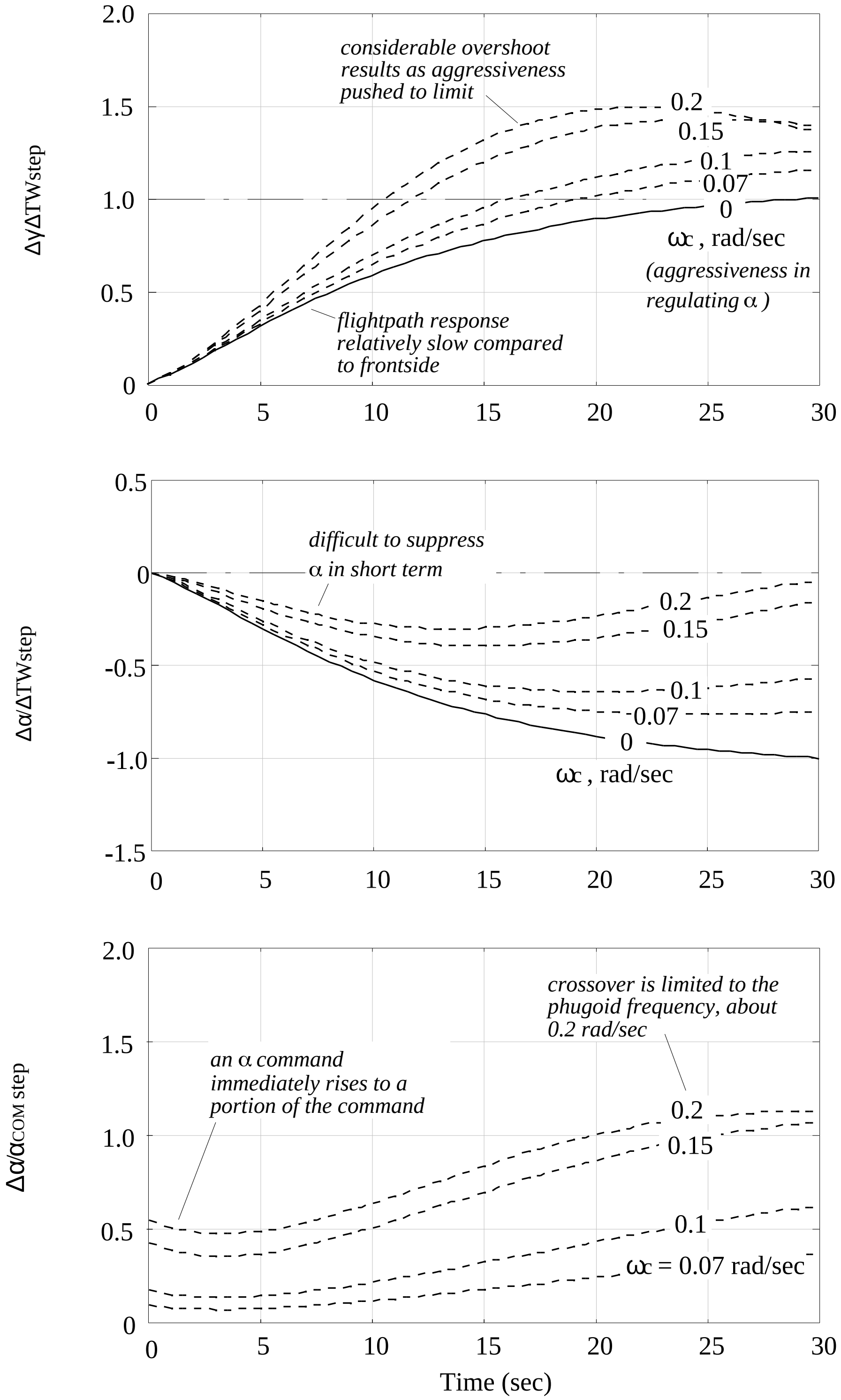


Figure 3-18. Response Survey for Backside Technique.

3.3.2 Compensatory Frontside Strategy (Attitude for Control of Flightpath)

The compensatory frontside gets a quick initial flightpath response but angle of attack regulation must still be limited to a fairly low value. In fact, with this strategy an angle-of-attack PIO condition is more severe than for the backside technique.

The basic control strategy, including angle-of-attack compensation is similar to the backside case as Figure 3-19 shows. Integral angle of attack is needed, but the optimum proportion is less,

$$K_I / K_\alpha \approx 1/T_{\theta 1} \text{ (rather than } \omega_p \text{)}.$$

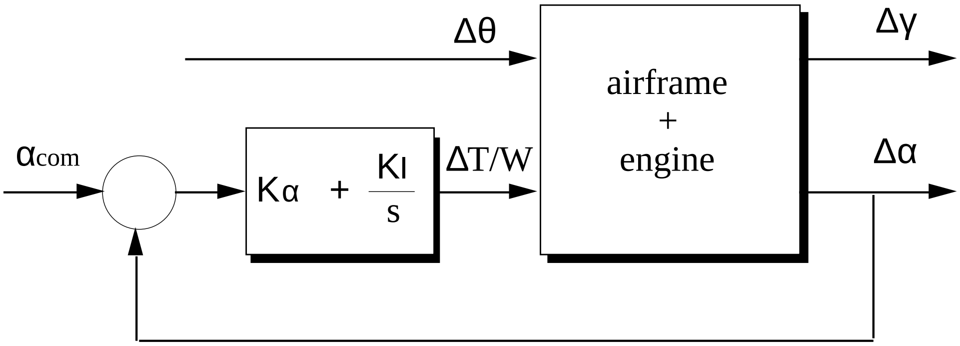


Figure 3-19. Diagram of Frontside Technique.

Figure 3-20 presents a survey of the frontside response characteristics. It shows that the level of aggressiveness needed for angle-of-attack regulation must be at least 0.2 to 0.3 rad/sec. However such values begin to result in large, undamped swings in angle of attack that tend toward instability. Thus, while there is the advantage of quick initial flightpath response, even for light angle-of-attack regulation, the general flightpath/airspeed control quality is not particularly good. Hence the pursuit technique takes on added importance.

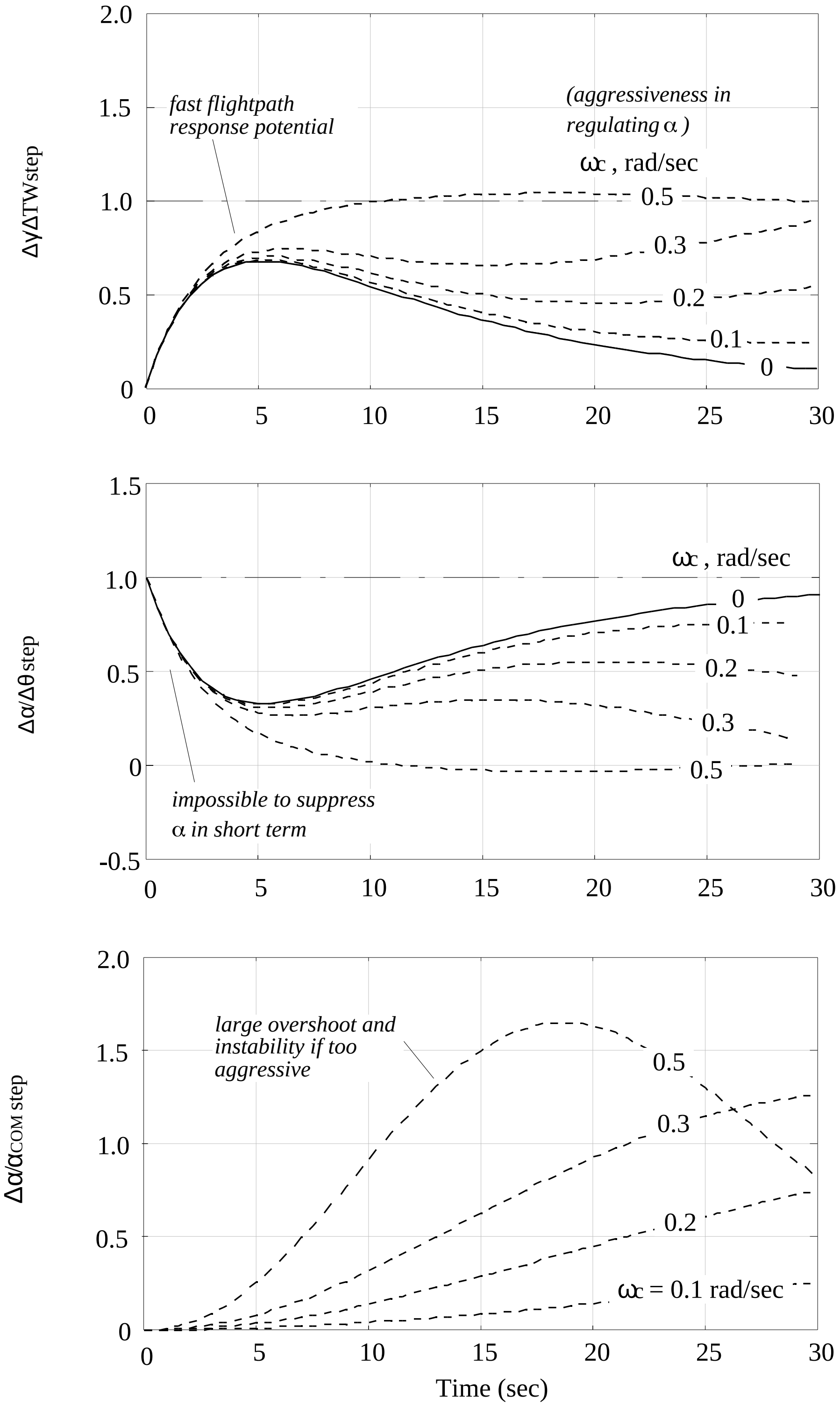


Figure 3-20. Response Survey for Frontside Technique.

3.3.3 Pursuit Strategy (Control of Flightpath with a Blend of Thrust and Pitch)

The pursuit strategy involves a blending of pitch attitude and thrust and is the natural result of the pilot observing the resulting responses from each of the two controls when applied one at a time. Figure 3-21 shows the block diagram, the main features of which are the crossfeed gain, K_{cf}, and the absence of any feedback loop around angle of attack.

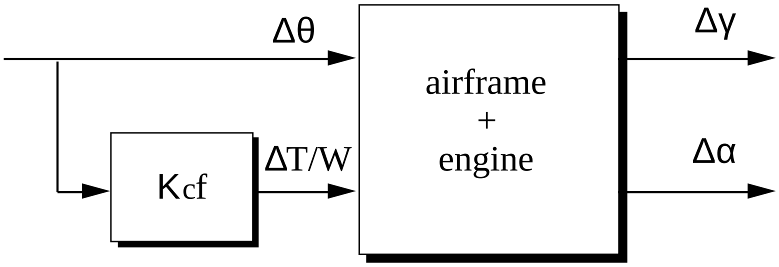


Figure 3-21. Diagram of Pursuit Technique.

For a flightpath change without upsetting the trim speed, the approximate proportion of incremental pitch attitude and incremental thrust-to-weight is about unity. For an angle of attack adjustment, the complement of this proportion is nearly optimum.

There are several ways to compute "optimal" crossfeed gains, depending upon the criteria considered. Three such criteria are illustrated here and include:

- K_{cf1}, the crossfeed to cancel the speed damping mode, $1/T_{\theta 1}$.
- K_{cf2}, the crossfeed to restore angle of attack in the long term.
- K_{cf3}, the crossfeed to null angle of attack following immediately a flightpath correction.

These can be computed according to the following expressions:

$K_{cf1} = T_{\theta 1} \cdot g \cdot Z_u / Z_\alpha$;

$K_{cf2} = g \cdot Z_u / V / \{ g/V \cdot [Z_u + X_u \cdot (\alpha + i_T) \cdot \pi / 180] \}$;

K_{cf3} is most easily obtained directly from a crossplot of $\Delta\gamma/\Delta\theta$step vs K_{cf} .

Figure 3-22 plots the values for these crossfeed as a function of approach speed. Note the consistency for the latter two and that all have values near unity. Also, it can be shown than the general behavior is nearly the same for other carrier aircraft.

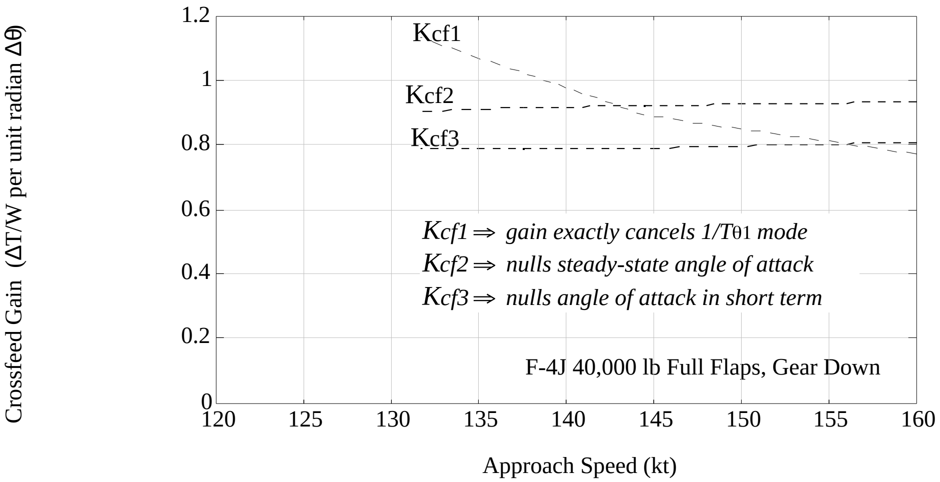


Figure 3-22. Crossfeed Gains for Several Optimality Criteria.

The main feature of interest in using the pursuit technique is in maximizing the short-term response time. Figure 3-23 shows how the effective rise times for the above crossfeed gains compare with the theoretical short-term response represented by both $T_{\theta 2}$ and its approximation based on $n_{z\alpha}$.

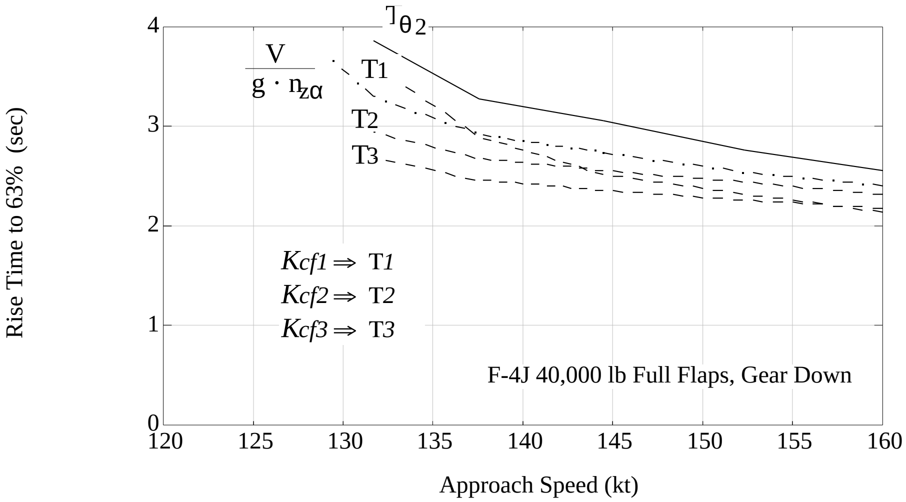


Figure 3-23. Effective Δ γ Rise Times for Several Optimality Criteria.

Figure 3-24 shows a response survey for the pursuit technique in terms of the step response for both flightpath and angle of attack for a family of crossfeed gains. Note the crossfeed values in terms of the optimum cases considered above.

The important features of the pursuit technique, therefore, is that the full flightpath response potential can be realized along with minimal angle-of-attack upset. Moreover, the pilot does not need to depend upon an active angle of attack feedback loop. Rather, there is a favorable first-order-lag kind of response for flightpath.

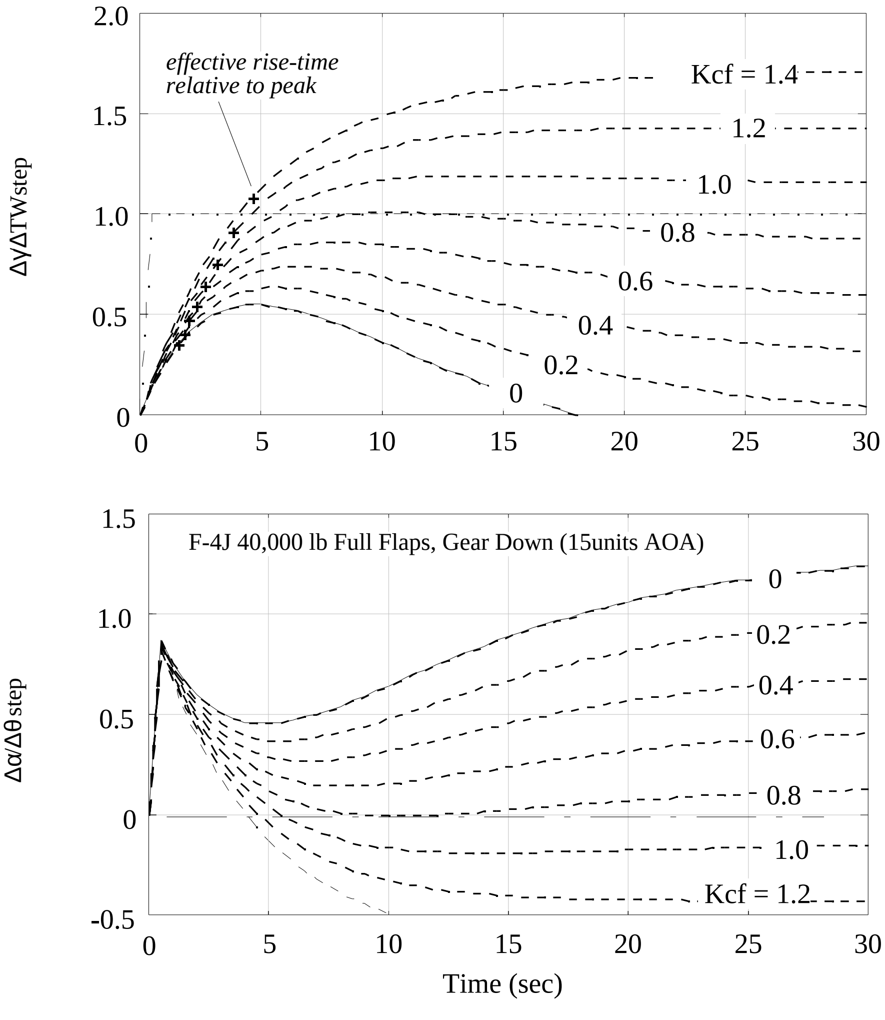


Figure 3-24. Response Survey for Pursuit Technique.

3.4 Audit Trail of Outer-Loop Control Factors

The above survey of dynamic response characteristics is the basis for tabulating individual features and examining their physical origin. Glideslope is the chief concern because the control factors are determined directly by the characteristics of the airframe, engine, and pilot technique. Angle-of-attack control factors are in essence dependent upon those features that define glideslope control and cannot be adjusted independently. Lineup control is mainly dependent upon kinematic and geometric relationships.

3.4.1 Glideslope and Angle-of-Attack Control

First, a list of basic control features can be constructed in view of the pilot-vehicle-task features as modeled above. Table 3-1 shows these elements followed by a brief discussion.

Table 3-3.
List of Outer-Loop Control Factors for GS and AOA Regulation.

1.	Steady-state flightpath authority (control power)	min $\Delta\gamma$ up and down
2.	Short-term flightpath response	max $\Delta\gamma$ rise time
3.	Cue availability (visual for this task)	GS and AOA visible
4.	Safety margins (for disturbances and use of controls)	α and V from stall
5.	Commensurate amounts of control (where coupling)	
6.	Control quickness	$\Delta\theta$, ΔT, Δ DLC
7.	Established technique	
8.	Quality of response (airspeed-flightpath cross coupling)	

Steady-State Flightpath Authority

Steady-state flightpath authority is the ability to sustain an adjustment in flightpath. It can be represented either by the steady-state flightpath angle or vertical velocity. It should be taken with respect to the prescribed on-glideslope flightpath angle and must include the ability to make both upward and downward corrections.

Because angle of attack is maintained in the long term, a sustained flightpath change corresponds to a net change in thrust-to-weight from the on-glideslope condition. Therefore maximum thrust bounds one extreme and minimum thrust the other. Under some conditions a speedbrake device might offer a means for modifying the thrust limits.

Short-Term Flightpath Response

The short-term flightpath response is a major limitation on the maximum-achievable aggressiveness in controlling flightpath. It can be a strong function of both the airframe lift and drag and of the pilot technique used.

Short-term response can be defined in several ways. Its main feature is the time required to obtain a significant amount of the peak response. This can be expressed in both the time and frequency domains. Perhaps the simplest and most useful metric is the *rise time* to some given level of the peak or steady-state value. The rise-time-to 63% is particularly popular because that factor can be viewed directly as the equivalent time constant for a first-order lag.

Cue Availability

Clear and timely cues are fundamental to any precise control situation. The carrier approach task relies upon visual display of glideslope and lineup from the FLOLS and deck geometry, respectively. The AOA indexer or HUD displays angle of attack directly.

Control cues also might be included under this item as they too are crucial to the outer-loop control task. Pitch and roll attitudes, both are implicit given that the ship is visible. Engine cue quality is not clearly defined. In some aircraft the engine noise is so subtle that unusual substitutes are sometimes used.[27] Forcing the pilot to refer to cockpit gages is an unacceptable choice because of the delay introduced in the control loop.

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[27] For example, in the A-7 without power indication displayed on the HUD, the pilot may use the change in air conditioner flow as a substitute cue for thrust change.

Safety Margins

Large-amplitude corrections must be made without encountering unsafe conditions. Normally aerodynamic stall is the main condition that is considered. There are at least two main safety problems. One is the need to absorb both normal and tangential gust components with minimal flightpath effects. The other is the ability to use the amount of pitch control necessary without excessive α excursions.

There may be other safety margins that need to be defined. For example, it may be appropriate also to view a thrust setting resulting in excessive engine lag as a safety-margin situation. This would be crucial where the pilot reduces power to steepen flightpath then must quickly add power to regain the desired flightpath angle.

Commensurate Amounts of Control

Whenever more than one control is involved in the management of a state variable, there must be amounts of each control available that is commensurate with the desired control authority. For example, the pursuit-level technique requires use of both pitch attitude and thrust to make a given flightpath angle change. Neither pitch nor thrust can be deficient.

The nature of control limits can vary. For example, a large upward flightpath correction might involve an excessive pitchup (too near stall) while more-than-adequate thrust is available. A large downward correction is more likely to encounter an aft throttle limit while nose down pitch is limited only to the available pitching moment.

Control Quickness

The outer-loop controls (pitch, thrust, bank angle) must be sufficiently quick for the pilot to use them in controlling an outer-loop control state. As a general rule-of-thumb, the response of the outer-loop control must be about three times faster than the desired closed-loop response.[28] For example, if a closed-loop bandwidth of 0.5 rad/sec is desired, the control should have a response of 1.5 rad/sec (or an effective lag of about 0.7 seconds).

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[28] This relationship can be shown analytically and has been observed empirically. It arises from the necessary tradeoff in closed-loop bandwidth and damping when there is a substantial lag or delay in a control mechanism compared to the dominant lag in the system being controlled. Reference 37 provides an explanation.

The pitch-response bandwidth or short-period requirements of the current flying qualities specifications represent a boundary on outer-loop control quickness for the pitch control. Thrust response is similarly bounded by V_{PA} criteria and will be discussed in Section 4.2.

The experience in development of flying qualities criteria has shown that any requirement on control quickness needs to factor in the qualities of the manipulator and of the display. This seems particularly crucial for the engine for which the throttle manipulator is a non-centering, high-friction device and the display ordinarily is subtle aural pitch and amplitude variations.

Established Technique

Several of the outer-loop control features depend upon the pilot technique. For example, Section 3.3 shows the dramatic difference in short-term response between compensatory frontside and backside techniques. Or, the use of DLC will generally produce different response features than pitch attitude. Therefore, the above outer-loop control factors need to be defined in terms of some reasonable control technique assumption.

Quality of Response

This category includes two main features that may not be satisfactorily covered by any of the other categories. For glideslope control these are speed damping, $T_{\theta 1}$, and backsidedness, $\partial\gamma/\partial V$. These qualities show up as long-term degradations in the response, generally seen as washout of flightpath response following a pitch control input.

The speed damping effect is a true washout effect and reflects how quickly the aircraft is convected axially due to aerodynamic and inertial forces. For an aircraft in the approach configuration, the response mode, $1/T_{\theta 1}$, covaries with the dominant glideslope mode, $1/T_{\theta 2}$. Therefore it is not particularly feasible to set independent standards. Nevertheless Reference 3 indicates that $1/T_{\theta 1}$, when varied, strongly influences pilot opinion.

The degree of backsidedness, as defined by $\partial \gamma/\partial V$ (or $1/T_{h1}$), is another aspect of the quality of response. The effect on the flightpath response is a faster decay, but more importantly perhaps, there is a destabilizing effect on flightpath and airspeed for a path control loop involving the pitch attitude control.

3.4.2 Lineup Control

The following is a tentative list of lineup control factors. The number of items is few because lineup control depends mainly upon coordinated-turn kinematics.

Table 3-4. List of Outer-Loop Control Factors for Lineup Regulation.

1.	Short-term lateral flightpath response	$\Delta\psi$, $\Delta\lambda$ or Δy rise time
2.	Cue availability (visual for this task)	deck LU information
3.	Control quickness	$\Delta\varphi$

Short-Term Lateral Flightpath Response

For a coordinated-turn regulation of lateral flightpath there is no direct analogy to heave damping in the short-term response. Instead there is only the net time for lateral flightpath to follow bank angle, given general amount of adverse yaw present. Most of the factors involved in this are a complex result of the roll and yaw moments produced by aerodynamics and the FCS. Use of a direct sideforce device would be a special case.

Cue Availability

Control of lineup requires visibility of the landing area and deck centerline relative to either the horizon or vertical dropline. In general, satisfaction of the FLOLS visibility requirement would be sufficient for lineup cues also.

Control Quickness

Control quickness for lineup equates to the inner-loop bank angle response characteristics. This will be a strong function of the natural roll damping or, if augmented in the roll axis, the artificial roll damping. Flying qualities requirements currently prescribe this characteristic.

4. ANALYSIS RESULTS BASED ON SYSTEM MATH MODEL

This section presents several analysis topics that provide insight into the carrier landing task and implications for design requirements not presently in effect. The topics include:

- Phase-plane analysis of flight data from simulated approaches
- Analysis of current Navy VPA criteria
- Computation of the "last significant glideslope correction"
- Inner-loop control lag influence on flightpath response
- Effect of engine lag on control of thrust

The analysis approach in each above case is simple yet yields substantial information about several aspects of outer-loop flying qualities. The phase-plane analysis permits a direct view of the closed-loop activity in glideslope control during actual landings. Next, the analysis of current approach speed criteria shows which design features are influenced—several important ones are not. The *last significant glideslope correction* is an approach for relating crucial features of the carrier landing task to pilot-vehicle system parameters. Then, the analysis of inner-loop control influence shows the relative importance of pitch attitude lag and thrust lag on the path-response potential. Finally, based on findings from the previous topic, engine lag is examined as an inner-loop problem based on the previous analysis topic. These analysis results combine to provide some direction for reexamination of existing design requirements and the need for additional research to fill gaps.

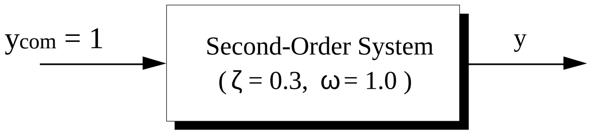
4.1 Phase-Plane Analysis of Flight Data

As a starting point, it is useful to examine the flight data examples of the simulated carrier approaches supplied by the Naval Air Test Center (presented earlier in Section 2). This illustrates how to extract easily information on pilot aggressiveness and maneuver amplitude, among other closed-loop features.

Background

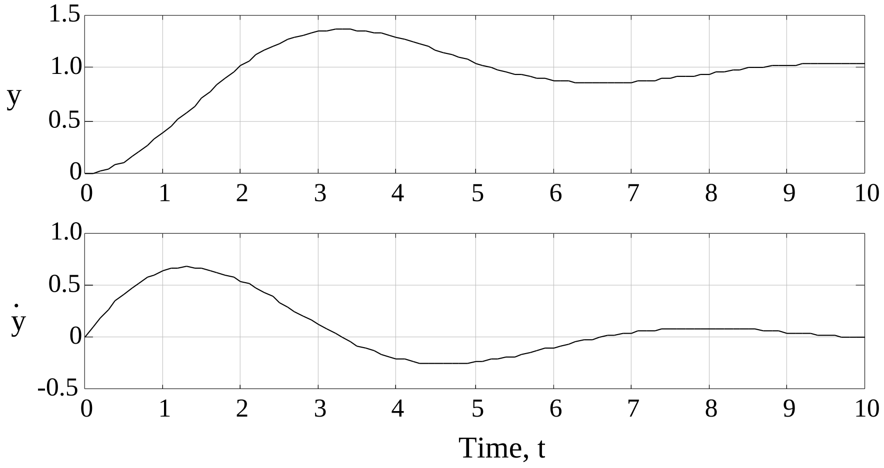
A phase plane is an alternative way to show time-history data for a dynamic system. The plot generally consists of rate-of-change of a state plotted versus the state itself. Time can be still be indicated. Figure 4-1 gives an example of how the step response of a second-order system can be shown in terms of both a time history and a phase plane.

a. Description of Dynamic System and Its State, y.



initial value of y is zero, commanded value is one at t > 0

b. Time-History of Response to Command.



c. Phase-Plane Portrait of Response to Command.

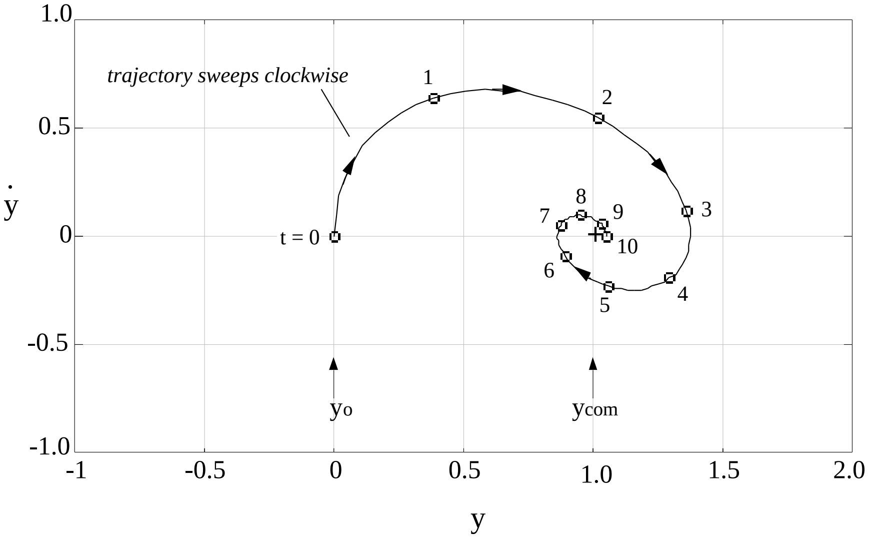
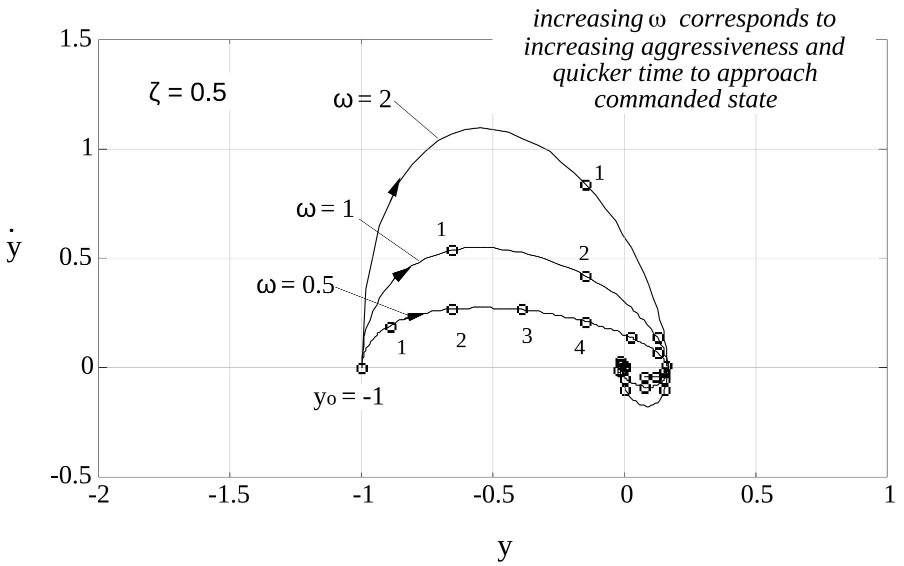


Figure 4-1. Example of a Second-Order-System Phase-Plane Portrait.

Aggressiveness and maneuver amplitude are two prominent features of a phase-plane trajectory for a discrete command. *Aggressiveness* appears as the proportion of height to width during a maneuver. Figure 4-2a illustrates this for a second-order system. *Maneuver amplitude* corresponds to the width of the trajectory as Figure 4-2b shows.

a. Indication of Varying Aggressiveness.



b. Indication of Varying Maneuver Amplitude.

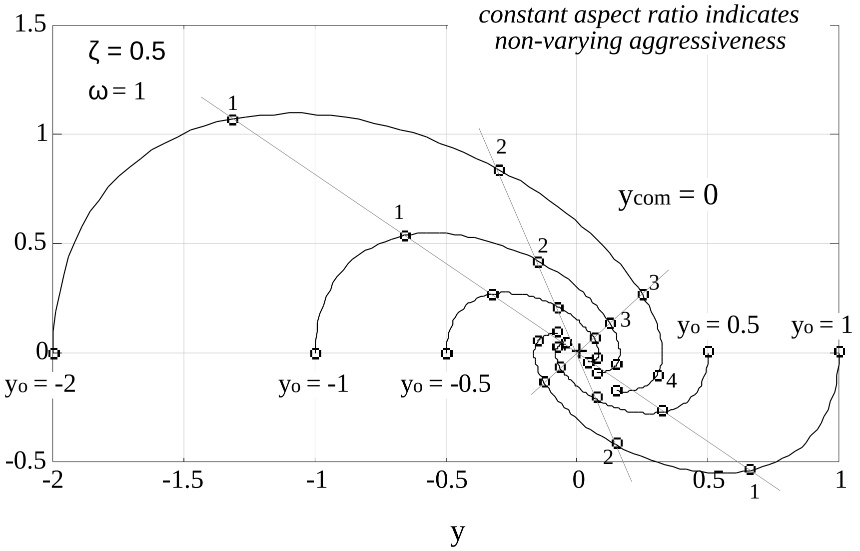


Figure 4-2. Appearance of Closed-Loop Attributes in the Phase Plane.

A phase-plane view of glideslope control is merely the crossplot of vertical velocity, $\Delta\dot{d}$, with glideslope displacement, Δd. One can show time, range, or any discrete events on the phase-plane trajectory, if desired.

A short sample of a glideslope correction was computed using the simple model shown in Figure 4-3. One can lump the dominant response modes as an integration in series with a lag. The integration represents the transfer function between vertical velocity and glideslope error; the lag lumps the heave damping and control lag with the implicit assumption of good pitch/thrust coordination. Two nonlinearities are included, one representing the amount of vertical velocity available (or tolerable to the pilot) and the other the limit of the FLOLS display range.

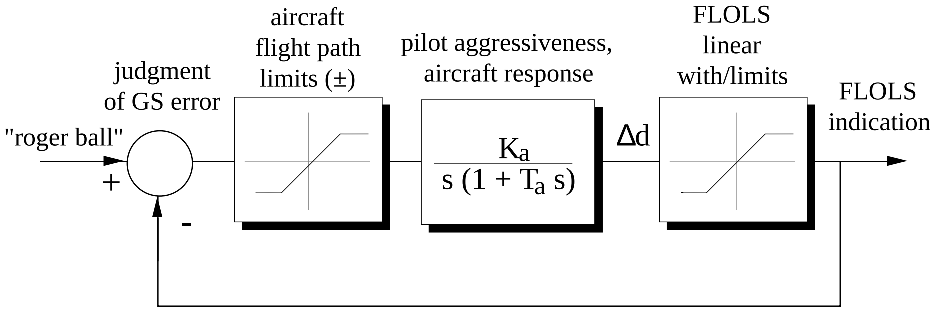


Figure 4-3. Glideslope Control Task Model.

Figure 4-4 shows the resulting phase-plane portrait of a correction based on the above model. Starting at 1000 ft from touchdown, the math-model pilot makes a six-second correction ending on-glideslope, but with slightly less than the nominal rate of descent (probably resulting in a long landing). The proportion of $\Delta \dot{d}$ to net Δd (indicating the aggressiveness of the maneuver) is about 0.35.

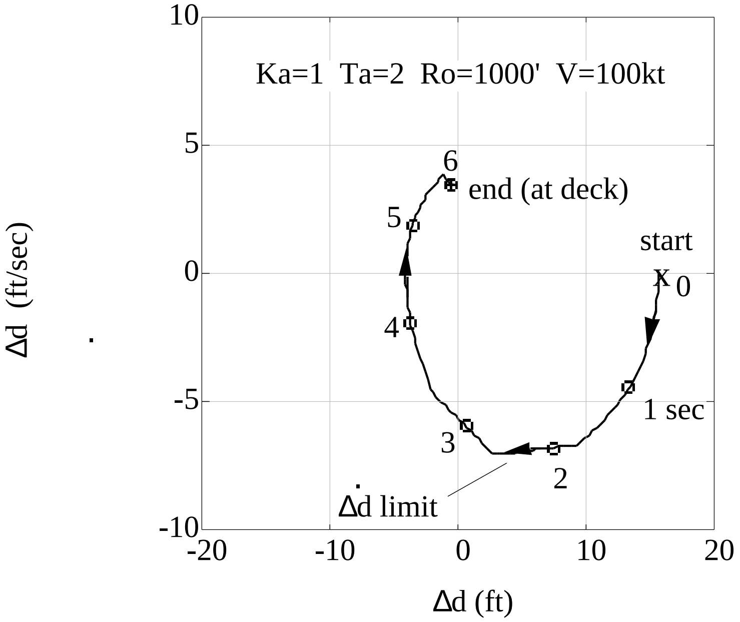


Figure 4-4. Phase-Plane Portrait of a Glideslope Correction.

<u>Application to Flight Data</u>

Several analysts have used this technique to examine the closed-loop control of aircraft. One notable study (Reference 60) compared airliner landings on simulators with actual landings to assess training effectiveness. Phase-plane analysis showed clear differences between flight and simulator in terms of aggressiveness, settling, amplitude, and consistency in the closed-loop landing flare.

Another study of Navy aircraft flying qualities applied the phase-plane analysis to a limited set of F-14 approach flight data describing a lineup maneuver(Reference 64). This was also reported in References 37 and 65. However, the lack of direct lineup position measurements detracted from the validity of the results.

The carrier landing data available for analysis in this study permit only a cursory inspection of characteristics owing to the small number of samples and because the landings were not made aboard an actual carrier but, rather, were field carrier landing practice. Nevertheless several aircraft are represented, and a few off-nominal conditions are included. The availability of high-quality laser-tracker position data greatly enhances the ability to observe several aspects of outer-loop control by the pilot, including task duration, aggressiveness, maneuver amplitude, and settling.

A-6 Approaches

Figure 4-5a shows the phase plane for the first of the A-6 approaches, a replot of the data presented earlier in Figure 2-23a. The pilot regulates glideslope precisely from the start of the data (about 1/2 nm) to the point at which he goes around.[29] Here it is not possible to discriminate between discrete adjustments (commands) or continuous tracking because the amplitudes are small. However, the level of aggressiveness indicated by the trajectory's height-to-width ratio compares well with subsequent cases where there are clear discrete commands.

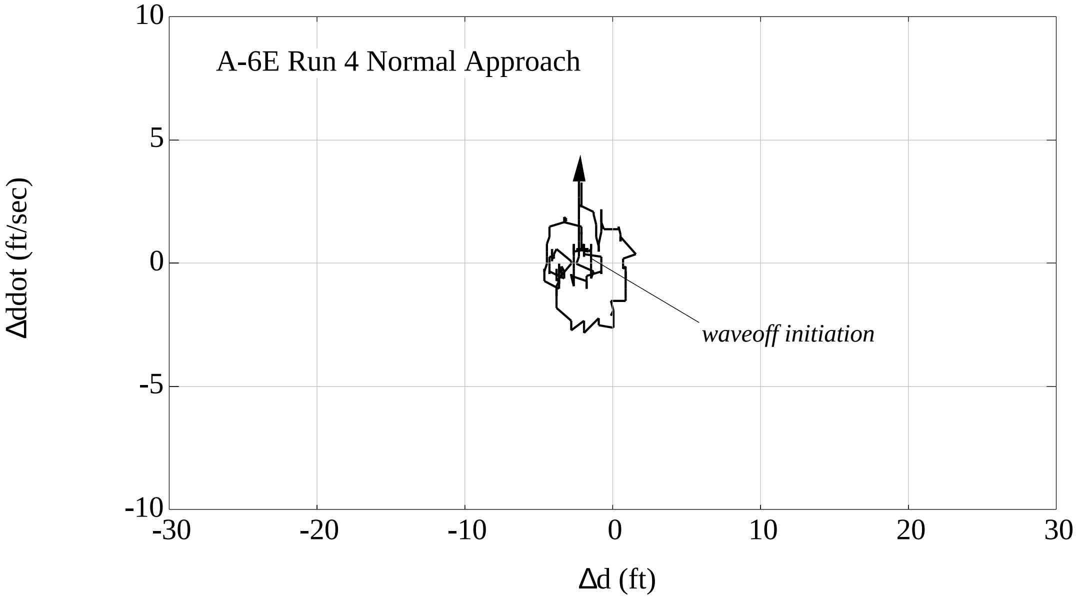


Figure 4-5a. Phase-Plane Portrait of A-6 Glideslope Corrections.

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[29] These approaches may have continued to touchdown. It is not clear in the data, but it also does not have any bearing on the pilot's control of glideslope during the approach.

Figure 4-5b (also Figure 2-23b) illustrates a discrete downward correction starting at about 2500 ft range and ending at 1000 ft range. The waveoff initiation begins at about 500 ft. The ratio of peak vertical velocity to height command is about 0.2, rather low compared to other cases. However, there is a hint of three stages of correction given by the three lobes in the phase plane. Taken individually, each lobe would indicate a more typical level of aggressiveness.

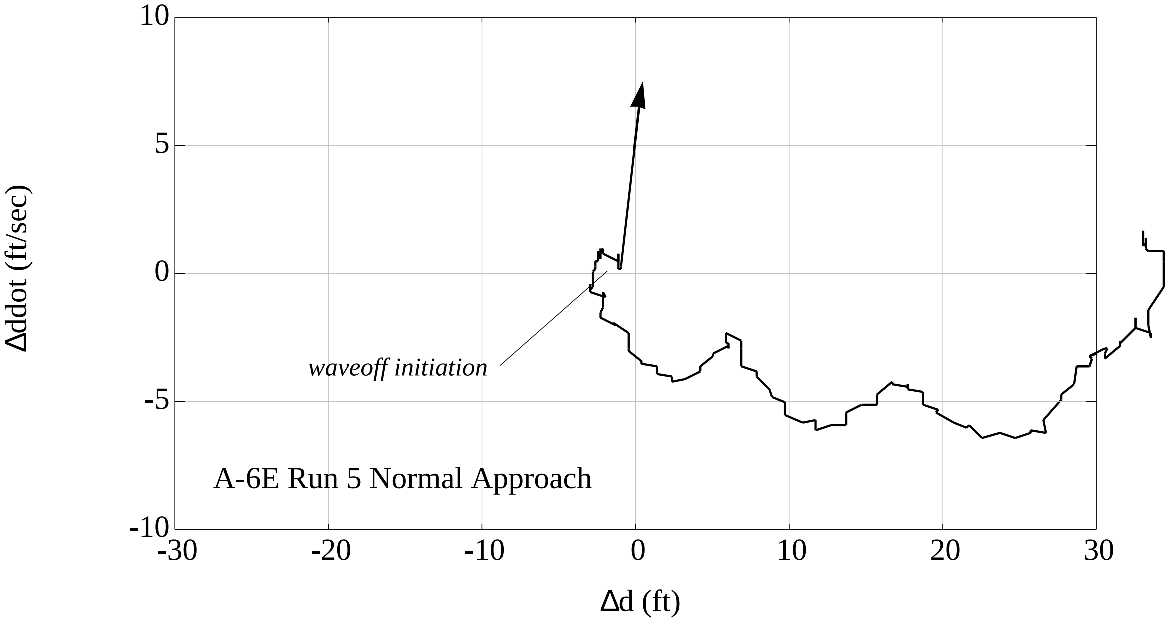

Figure 4-5b. Phase-Plane Portrait of A-6 Glideslope Corrections.

Figure 4-5c (also Figure 2-23c) shows a high, slightly steep descent beginning at 3500 ft range and a fairly aggressive return to glideslope at 2500 ft. Tight regulation continues for the remainder of the approach. Figure 4-5d (also Figure 2-23d) shows a two-step correction from a slightly low condition.

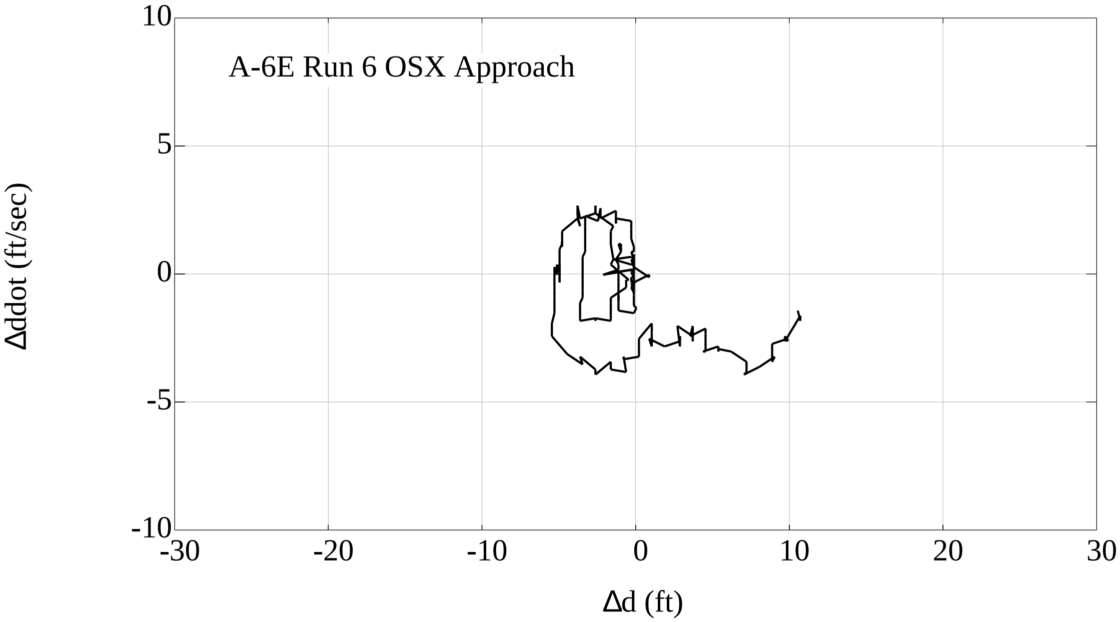

Figure 4-5c. Phase-Plane Portrait of A-6 Glideslope Corrections.

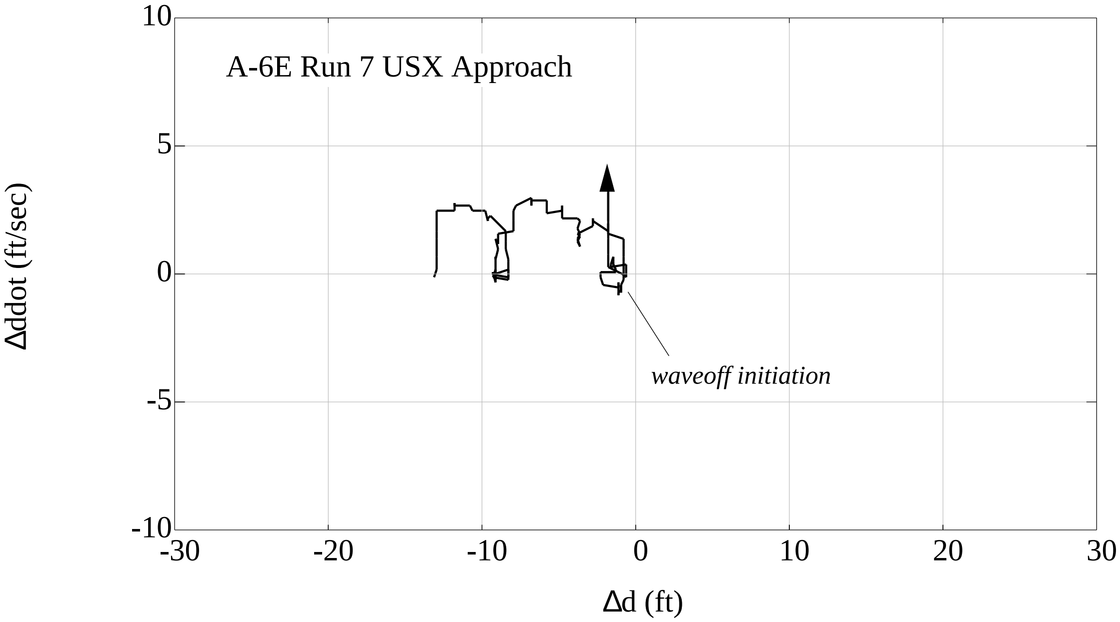

Figure 4-4d. Phase-Plane Portrait of A-6 Glideslope Corrections.

Figure 4-5e (also Figure 2-23e) illustrates a large correction from a low condition followed by tight tracking about the glideslope.

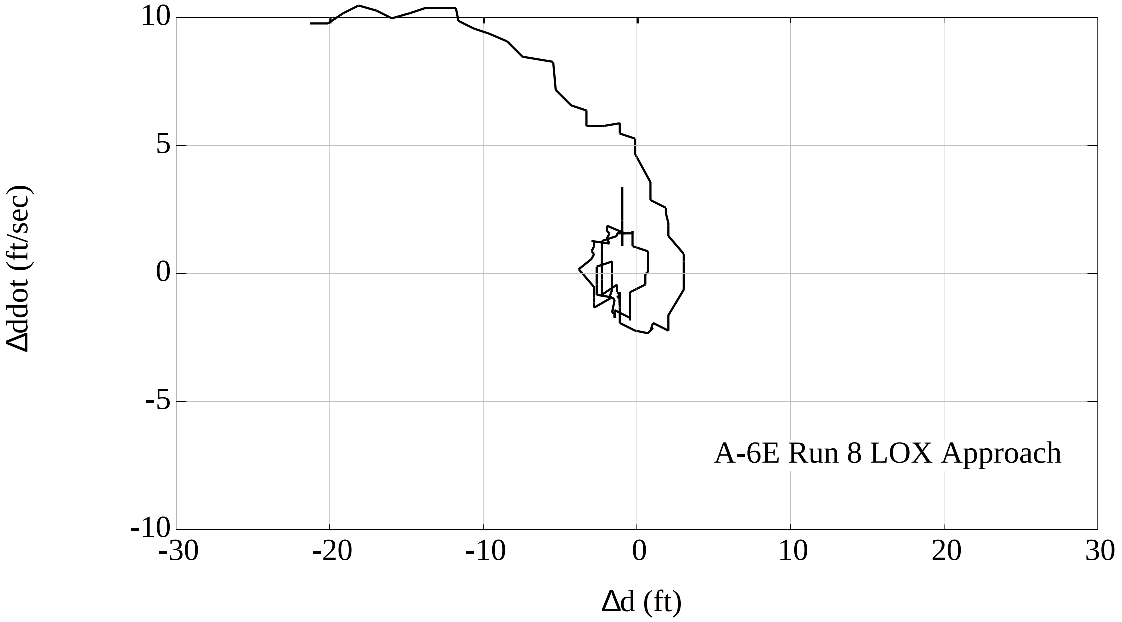

Figure 4-5e. Phase-Plane Portrait of A-6 Glideslope Corrections.

Figure 4-5f (also Figure 2-23f) shows a large intentional transition to a high position in the middle followed by fine corrections back to the glideslope.

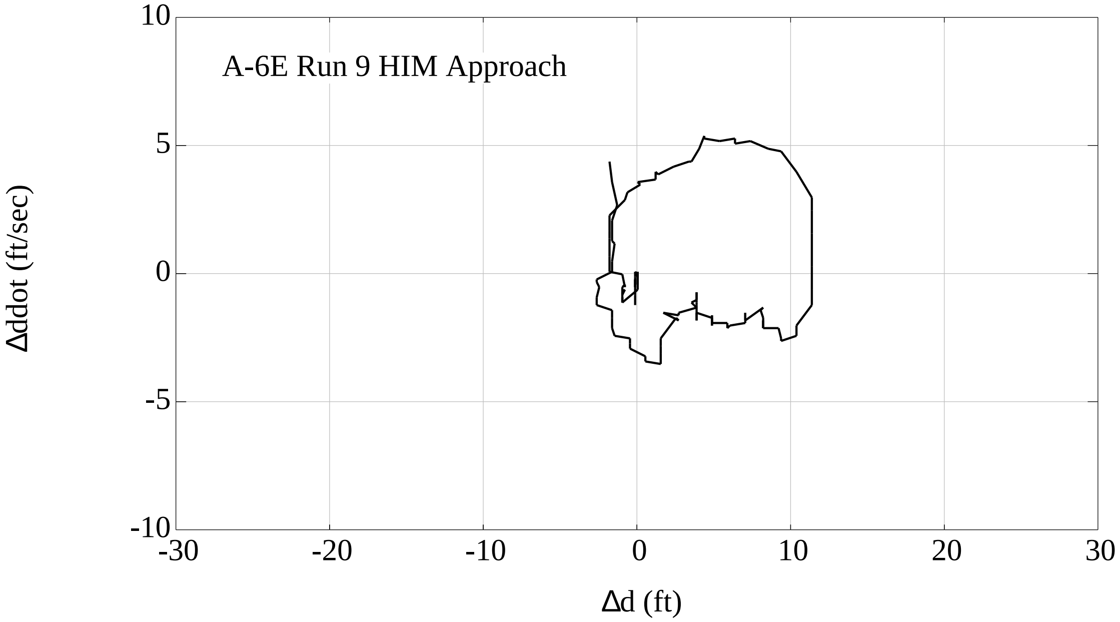

Figure 4-5f. Phase-Plane Portrait of A-6 Glideslope Corrections.

F-14 Approaches

The next set of phase planes represents two F-14 approaches. Figure 4-6a is a slow recovery from a low position followed by an oscillatory regulation of glideslope. The first part has some higher-frequency content yet three discrete corrections are visible. The second part is oscillatory and suggests some PIO yet damps at the end. Figure 4-6b portrays a continuing downward set of corrections.

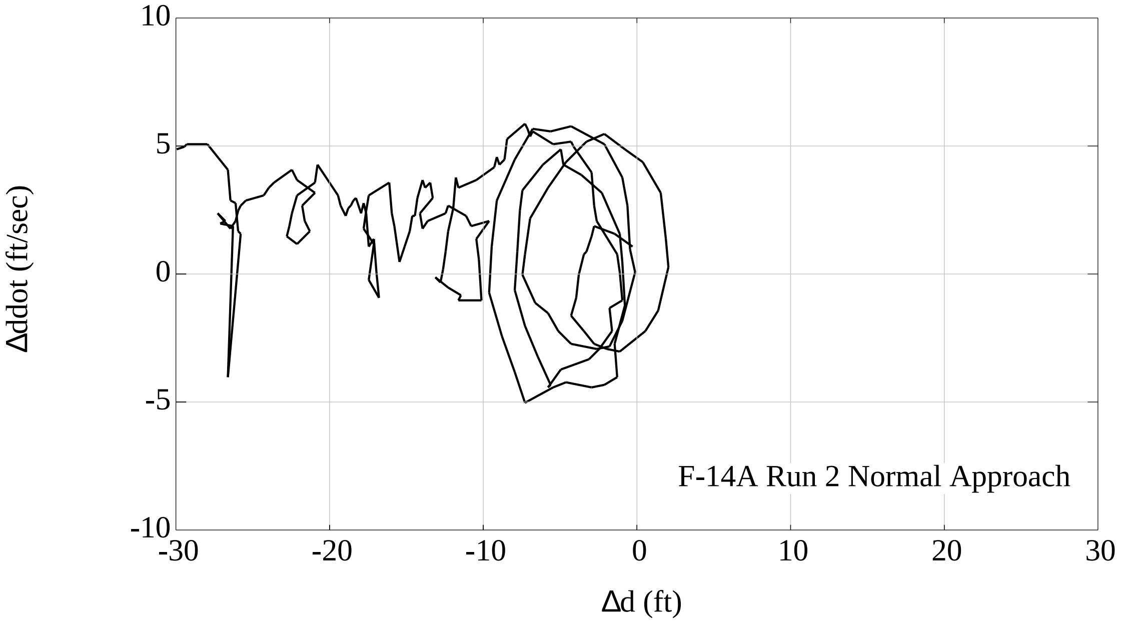

Figure 4-6a. Phase-Plane Portrait of F-14 Glideslope Corrections.

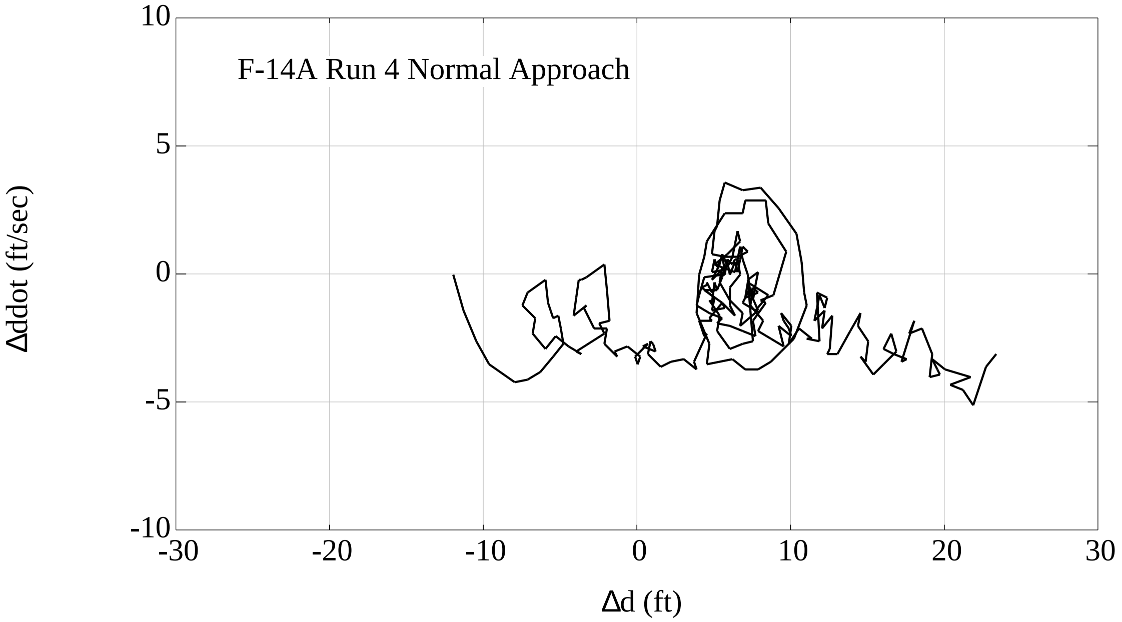

Figure 4-6b. Phase-Plane Portrait of F-14 Glideslope Corrections.

F-18 Approaches

Figure 4-7 shows a set of four F-18 approaches. The phase-plane trajectories are smoother than in most of the previous ones. This may be related to pilot technique or just slightly better quality position measurements. All the cases show fairly precise control of glideslope.

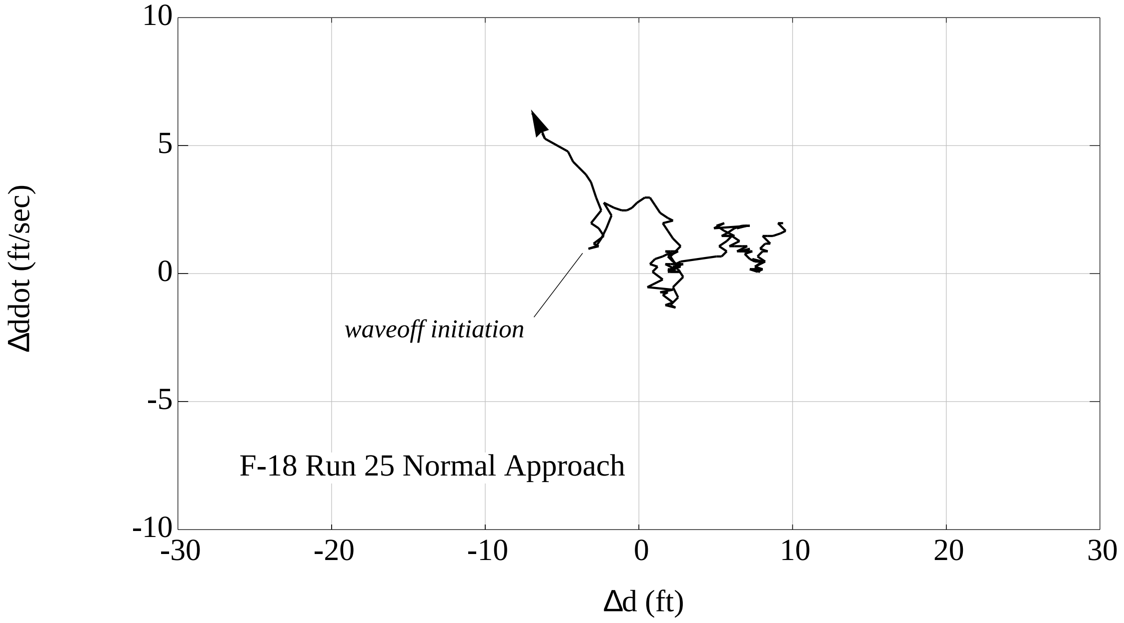

Figure 4-7a. Phase-Plane Portrait of F-18 Glideslope Corrections.

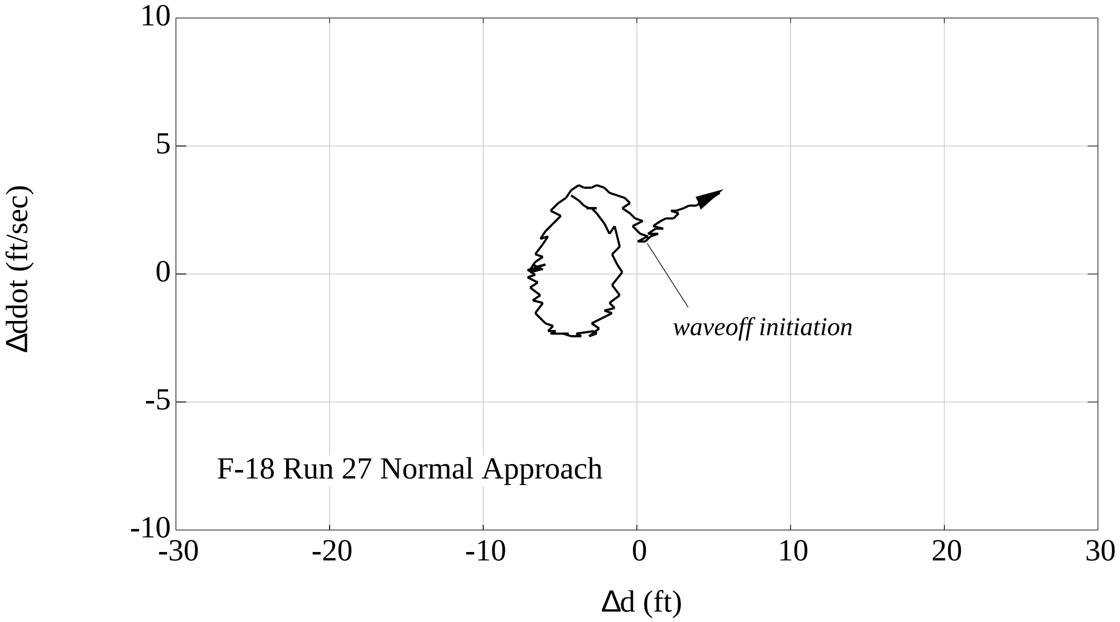

Figure 4-7b. Phase-Plane Portrait of F-18 Glideslope Corrections.

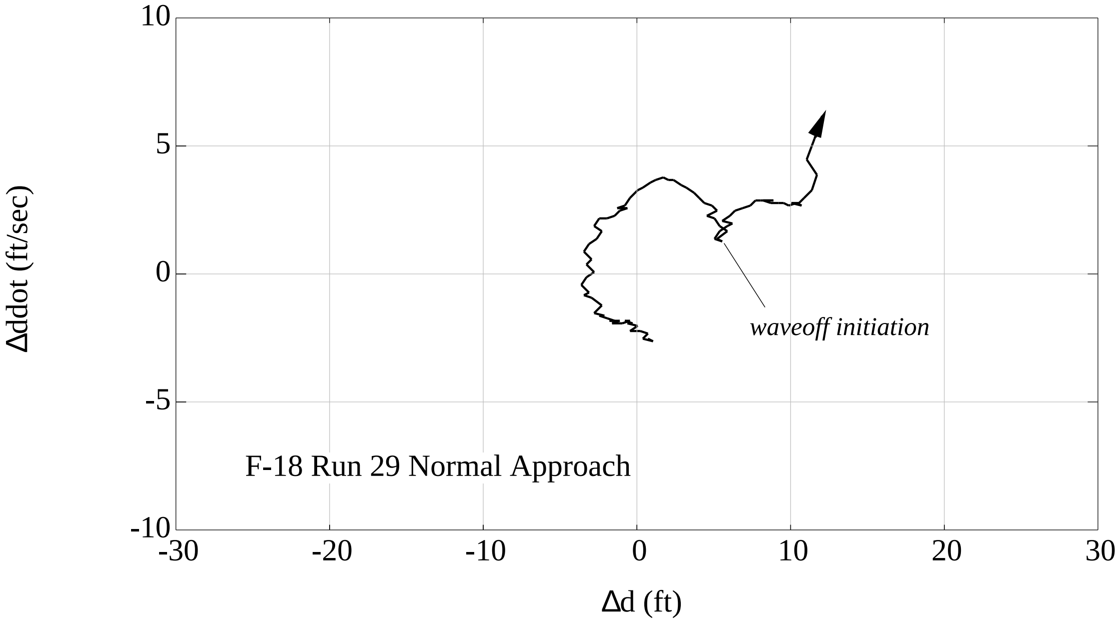

Figure 4-7c. Phase-Plane Portrait of F-18 Glideslope Corrections.

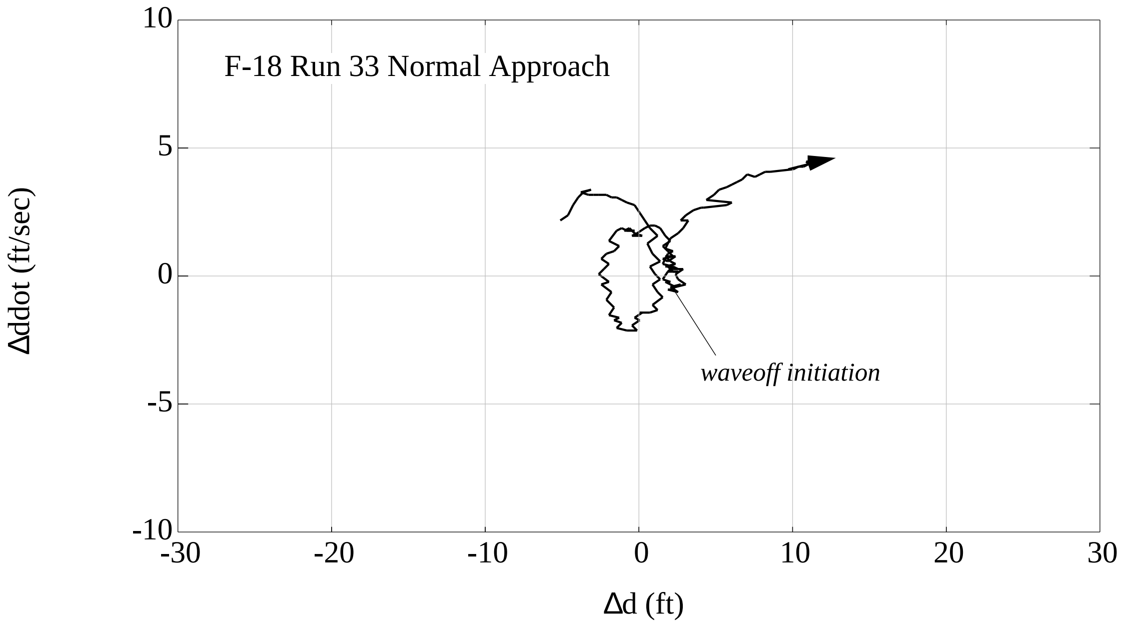

Figure 4-7d. Phase-Plane Portrait of F-18 Glideslope Corrections.

T-45 Approaches

Figure 4-8 shows two T-45 approaches. The first is a tight regulation of glideslope similar to most of the previous cases. Figure 4-8b shows a gradual exponential acquisition of the glideslope from a very high position, a loose, unaggressive kind of closed-loop activity.

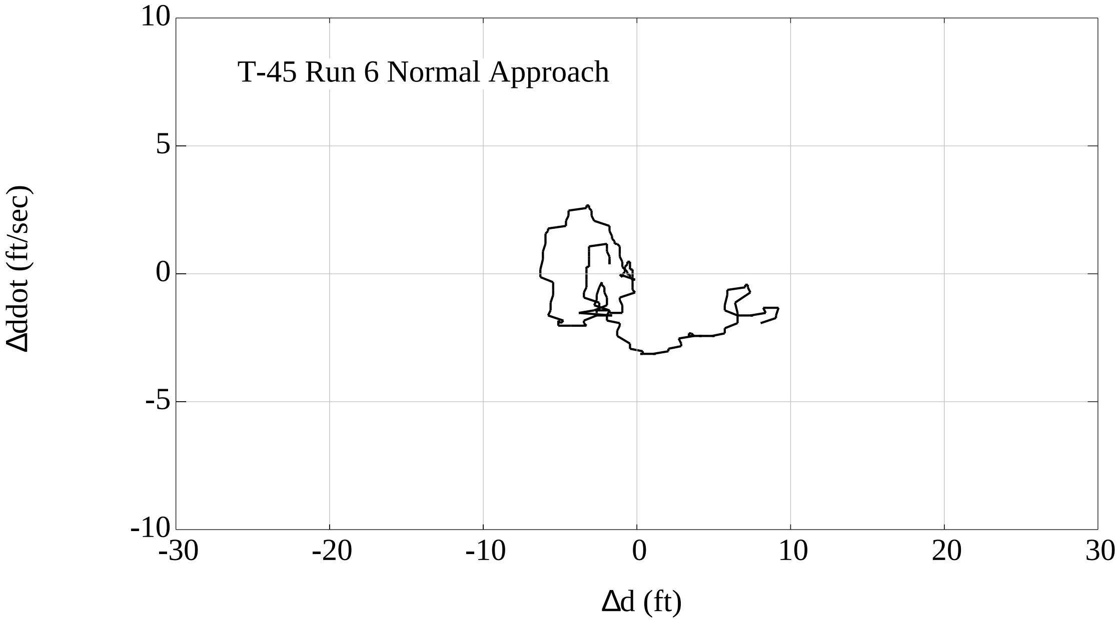

Figure 4-8a. Phase-Plane Portrait of T-45 Glideslope Corrections.

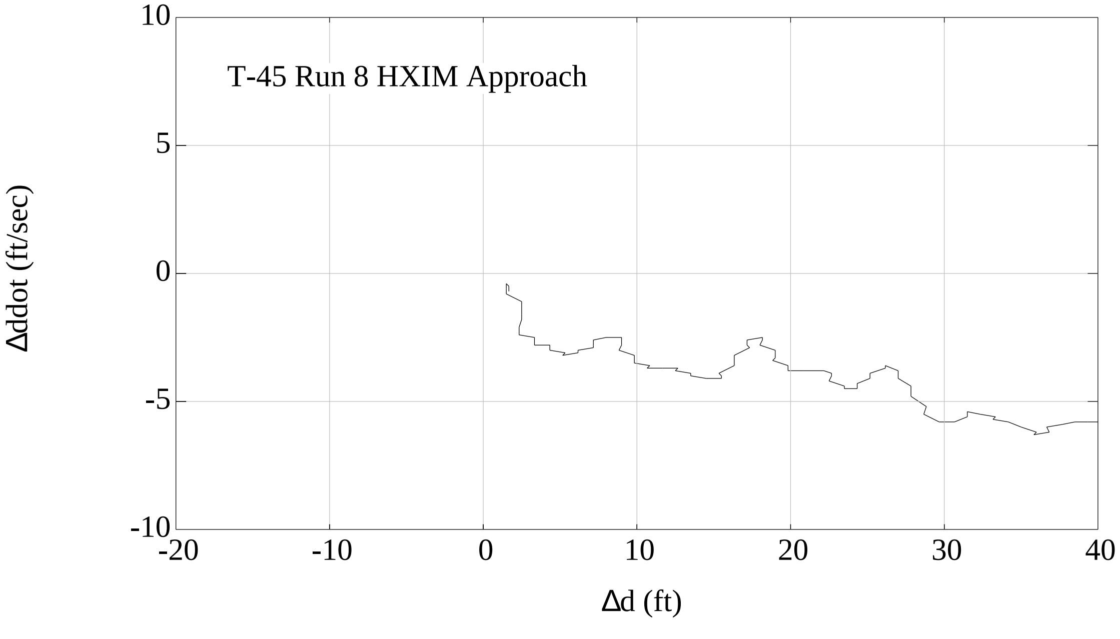

Figure 4-8b. Phase-Plane Portrait of T-45 Glideslope Corrections.

The foregoing examples indicate similar closed-loop activity among all the aircraft and over the magnitude of corrections. Further detailed analysis of these data could be performed following the procedures described in Reference 60, but this would not provide any additional insight for two reasons. One is that there is no detailed pilot commentary available for the above approaches, therefore some analysis of control behavior would only be speculative. The second reason for not doing further analysis is that these were only simulated carrier approaches to a field. Actual carrier landings would provide far more credibility of analytical results. Nevertheless, the above data do provide a starting point for assessing the true nature of actual outer-loop control for current Navy aircraft for the landing task.

Further, more detailed analyses of carrier approach data are needed, though, to obtain good quantification of task performance for setting rational design requirements. All three outer-loop control tasks need to be addressed. For approach data being gathered, the pilot and the LSO need to assess and discuss individual corrections in each axis, particularly their criticality with respect to the terminal condition. Inner-loop data also must be monitored to establish pilot technique.

4.2 Analysis of V_{PA} Criteria

The V_{PA} criteria, including the popup maneuver, are the main requirements set by the Navy to ensure adequate glideslope and angle-of-attack control characteristics for carrier aircraft. It is worthwhile, therefore, to review these criteria and their effect on shaping outer-loop response features.

Section 1 gave an introductory discussion of the Navy approach speed criteria. Below is a more detailed statement of them followed by an analysis of each of their implications for outer-loop control. The objective is to identify what outer-loop control factors are effectively guaranteed and where there are gaps. The list of necessary factors presented earlier in Section 3.4 is useful in making this determination.

4.2.1 Statement of Criteria

The Navy approach speed criteria are stated below from Reference 5, the F/A-18 system specification. It is a reasonably recent version of the various sets of requirements used by the Navy since the early 1960's.

Navy Approach Speed Criteria

With the aircraft in the landing configuration and on a 4° glideslope on a 89.8° F day, the approach speed, V_{PA} , shall be the highest of the airspeeds defined by the following:

a. The lowest speed at which it is possible to achieve a level flight longitudinal acceleration of 5 ft/sec^2 within 2.5 sec after initiation of throttle movement (to MIL thrust) and speedbrake retraction.

b. V_{SPA} x 1.1 where V_{SPA} is the power-on stall speed using the thrust required for level flight at 1.15 V_{SL}, the power-off stall speed.

c. The lowest level-flight speed at which the pilot, at the design eye position, can see the stern of the carrier at the waterline when intercepting a 4° glideslope at an altitude of 600 ft. The origin of the glideslope is 500 ft forward of the stern and 63 ft above the waterline.

d. The lowest speed at which all stability and control requirements are satisfied (MIL-F-8785C).

e. The lowest speed at which the aircraft is capable of making a glide path correction from stabilized flight at V_{PA} to a new glide path 50 ft above the original glide path within 5 sec after initiation of the maneuver. The maneuver shall be performed without change in thrust settings, and the aircraft angle of attack during the maneuver shall not exceed that necessary to achieve 50% of the maximum positive delta load factor available, based on static lift coefficient, at the initiation of the maneuver. Control rate input for simulation of V_{PA} shall not exceed control system limits. The maneuver shall be considered complete when a glide path correction of 50 ft has been reached. After completion of this maneuver, the aircraft shall be capable of maintaining a new glide path at least 50 ft above and parallel to the initial glide path, with the pilot permitted to change thrust setting as required.

f. To ensure rapid aircraft response to step throttle commands corresponding to ± 3.86 ft/sec^2 (± 0.12 g) longitudinal acceleration, such throttle inputs shall result in achieving 90% of the commanded acceleration within 1.2 sec. This requirement shall apply in the approach configuration throughout the range of all throttle settings required for operations over the usable approach configuration weight/drag levels while trimmed on a 4° glideslope.

Each item listed above is more or less significant to the general specification of an acceptable approach speed because of the collective constraint and limitation of a variety of outer-loop control features. This is demonstrated in the analysis of each item presented next.

4.2.2 Implications of Requirements on Airframe/Engine Characteristics

The V_{PA} requirements imply several characteristics for the outer-loop dynamics of the airframe/engine system. This is shown by rearranging the order of items then illustrating the implied constraints and limitations by analysis based on the math models presented in the previous sections.

Analysis of the approach speed criteria shows that they restrict several outer-loop control factors, but sometimes in indirect ways. One criterion, the popup maneuver, may not set the strong constraint on flightpath response that the requirement seems to suggest. Also, the short-term axial acceleration criterion may suffer from ambiguity in its wording thus compromising its important implication for the quickness of thrust response.

Satisfaction of Stability and Control Requirements in MIL-F-8785C

There are several requirements in both of the existing flying qualities specifications, MIL-F-8785C (Reference 2) and, the more recent MIL-STD 1797A (Reference 1),[30] that support the Navy approach speed criteria. Most of these supporting requirements influence inner-loop pitch attitude control. There are some which address outer-loop flightpath and speed control, but may not be particularly effective, especially for the carrier landing task. There are no requirements that ensure the quality of thrust control.

Both the above specifications cover the basic inner-loop pitch axis flying qualities in depth. This includes pitch-attitude response to the control stick and the stick feel characteristics. Attitude response includes control bandwidth, damping, control power, and control forces. There are provisions for complex high-gain stability and control augmentation systems as well as for a basic unaugmented airframe.

Beyond such inner-loop requirements there are some that appear to have outer-loop implications but are still open to question. Section 1.2.1 described these. The one outer-loop weakness that should be stressed is the minimum allowable short-term flightpath response. It is not defined in MIL-F-8785C and done in MIL-STD 1797A with insufficient justification by its lower bound on $1/T_{\theta 2}$.

There is some belief that the ω_{sp} versus $n_{z\alpha}$ boundaries, common to both of the specifications, address outer-loop flightpath control. The allowable band of ω_{sp} that is

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[30] MIL-STD-1797A is addressed here in order to anticipate its future application to Navy carrier aircraft.

expressed as a function of $n_{z\alpha}$ is based on the Bihrle Control Anticipation Parameter (CAP) criterion originally proposed in Reference 66. CAP, strictly interpreted, is the ratio of the instantaneous angular pitching acceleration per unit of the eventual steady-state load factor. Therefore, it is a kind of inner-loop/outer-loop control-harmony metric, and therefore is a beneficial feature supporting the approach speed criteria. But it does not determine how quickly flightpath responds to an attitude change, nor does the lower limit on $n_{z\alpha}$ as one can see from inspection of the approximate factors in Section 3.

One additional, and general, shortcoming of the traditional flying qualities requirements is their lack of any accompanying conditions on piloting technique. Prior analysis has already shown how outer-loop control performance depends upon the specific technique used. For example, there should be an expectation that pitch attitude response criteria may depend upon the role of attitude in controlling flightpath.

In summary, the current role of flying qualities specifications is simply to provide a suitable pitch attitude control capability. There is, however, a potential for effective coverage of outer-loop response characteristics, particularly short-term flightpath response.

Longitudinal Acceleration of 90% of ± 3.86 ft/sec^2 Within 1.2 Seconds

This requirement affects two crucial outer-loop control factors. First, it sets a maximum engine response time constant over the range of flightpath angle excursions likely to be used during an approach. Second, it sets the level of flightpath control authority ($\Delta \gamma$), both upward and downward.

The implication for engine response, unfortunately, is subject to two possible interpretations depending upon the definition of “commanded acceleration.” If this refers to the virtual acceleration without airframe speed damping, then the commanded acceleration simply is equal to the Δ T/W ratio. On the other hand, if the commanded acceleration includes airframe speed damping then there is no near-term, steady-state acceleration. Instead there is a peak acceleration followed by a washout as drag force builds against the thrust force. Consider each of these cases.

The first case is simple. Only the net thrust force is considered and the 1.2 sec requirement applies to the point at which thrust increases (or decreases) to 90% of the new steady-state value. Assuming a first-order lag response shape (i. e., exponential), this requirement equates to an engine lag time constant, T_{eng}, of 0.52 sec.[31] Further, it applies for net Δ T/W changes spanning ± 0.12.

The second case is more complex and requires the computation of axial acceleration. The Δa_x response transfer function, using the nomenclature presented in Sections 1 and 3, is given by:

$$\Delta a_x(s) = \frac{s\, N^{u}_{T/W}}{\Delta} \cdot \Delta T/W(s)$$

where Δ T/W is a step throttle command applied to an engine having an effective first-order lag time constant of T_{eng}.

By inspection, the approximate factors yield:

$$\Delta a_x(s) = \frac{\overset{\text{washout}}{g \quad s} \quad \overset{\text{cancellation}}{\cancel{(s - Z_w - \eta X_w)}}}{(s + 1/T_{\theta 1}) \quad \cancel{(s + 1/T_{\theta 2})}} \quad \overset{\text{lag}}{\frac{1}{(T_{eng}\, s + 1)}} \cdot \Delta T/W(s)$$

Thus, the airframe response component essentially is a slow washout of a_x with a time constant of $T_{\theta 1}$, and the dominant response mode is the engine lag, T_{eng}. Figure 4-9 shows an example for an airframe with a typical 10 sec speed-damping time constant ($T_{\theta 1}$) and an engine with a 0.5 sec lag (T_{eng}). For a unit thrust command, the airframe acceleration builds to a peak then begins to decay.

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[31] Neglecting the airframe contribution, the thrust rise-time-to-90% can be converted to an effective first-order time constant by dividing by a factor of -ln(.1), or 2.3. Thus the 1.2 sec rise time is equivalent to a first-order time constant of 0.52 sec.

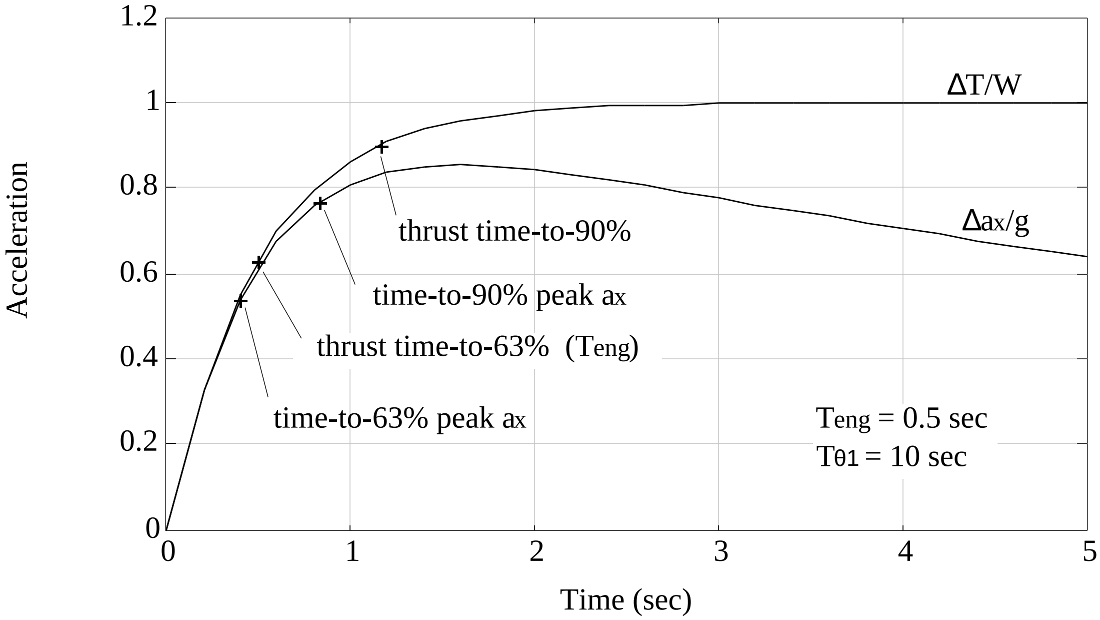

Figure 4-9. Acceleration Response to a Unit Δ T/W Command.

If the term “commanded acceleration” refers to the airframe Δa_x, is it the peak value of Δa_x or is it the virtual acceleration represented by the unity value Δ T/W? In the former case the time to 90% of the peak Δa_x is 0.84 sec, but in the latter case a value of 90% is never reached. The use of the peak Δa_x thus seems a reasonable assumption for definition of commanded acceleration. But this results in permitting and effective engine lag of 0.8 sec rather than 0.52 sec for the previous case.[32]

The case described here suggests that it is crucial to have a precise definition for commanded acceleration, or, if engine lag is really the main intent of the requirement, specify it directly. The consequence may be to permit excessive engine lag.

The second implication of the requirement, as it is expressed above, is to ensure a minimum amount of flightpath angle authority. The acceleration of 3.86 ft/sec^2 converts to 0.12 g, or alternatively, an incremental thrust-to-weight ratio of 0.12. This is equal to a steady-state flightpath angle change of about ± 7° .[33]

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[32] This was determined by computing the time to 90% of the peak Δa_x for the speed damping value used in the above example.

[33] The linearized equations of motion show that, for constant $\Delta\alpha$: $\Delta\gamma = [1 + C_D/C_L \cdot \eta] \cdot \Delta T/W$.

One should note that the basic requirement applies only to thrust changes made relative to the nominal glideslope flightpath angle, however. It does not require that the engine thrust lag be as fast when making an upward correction from steeper descent conditions. This could result in an excessively slow flightpath response back to the nominal flightpath angle in view of the tendency for longer engine lag at low thrust settings shown in Section 2, especially for turbofan engines.

Level-Flight Acceleration of 5 ft/sec^2 Within 2.5 Seconds

The 5 ft/sec^2 longitudinal acceleration within 2.5 sec provides an upward flightpath control power capability, but sets no additional constraint on the thrust lag time constant. The requirement generally permits use of military thrust and retraction of speedbrakes, thus it applies to a waveoff condition. The Δa_x time history given in the previous example shows that at 2.5 sec the axial acceleration has probably peaked and is beginning to washout due to airframe speed damping. There do not appear to be critical implications with respect to approach flightpath control factors.

Correction in Glidepath of 50ft Within 5 Seconds (Popup Maneuver)

One is tempted to regard the popup maneuver to have direct implications for airframe flightpath response. For example, it would be natural to expect that the popup maneuver reflects explicitly a short-term response capability. However, careful analysis of the effect of various design parameters on popup maneuver performance reveals a general insensitivity to most of the parameters in the $\Delta\gamma/\Delta\theta$ response function. The main factor in performing the popup maneuver is the ratio of approach speed to stall speed, V/V_{SPA}. The following paragraphs demonstrate this.

All the main features of the popup maneuver are contained in the linear transfer function for height, Δd, due to a change in attitude, $\Delta\theta$:

$$\Delta d = \frac{V \cdot N_{\theta}^{\gamma}}{s\,\Delta} \cdot \Delta\theta$$

Careful inspection using the approximate factors listed in Sections 1 and 3 proves that all the factors in this transfer function can be determined from the parameters V, $n_{z\alpha}$, and $\partial\gamma/\partial V$. Next, the pitchup maneuver, $\Delta\theta$, is defined by the stall margin, V/V_{SPA}, $n_{z\alpha}$, and the way in which the pilot applies the pitchup to the maximum allowable α (abruptly, slowly, etc.).[34] The peak incremental α excursion permitted during the popup maneuver corresponds to one-half the remaining aerodynamic lift and is given by:

$$\text{peak } \Delta\alpha = \frac{\left[\left(\frac{V}{V_{SPA}}\right)^2 - 1\right]}{2\, n_{z\alpha}}$$

Any pitch-control time history sequence (elevator or longitudinal control input) is permitted so long as the peak $\Delta\alpha$ limit is satisfied.

The following is an analysis of how the basic design parameters named above influence the popup maneuver performance. First, Figure 4-10 shows the popup maneuver response for a nominal set of conditions typical of existing carrier aircraft:

- normal-acceleration sensitivity to angle of attack, $n_{z\alpha} = 3.5$ g/rad
- neutral backsidedness, $\partial\gamma/\partial V = 0$
- power-on stall margin, $V/V_{SPA} = 1.2$
- rapid attitude step with a min-bandwidth control system, 0.4 sec lag pitch step[35]
- approach speed, V = 125 kt

The resulting height response is predominantly ramp-like with an initial lag. For the nominal values chosen, the time to 50 ft is about 5 sec (4.8 sec). Hence this would satisfy the V_{PA} criterion.

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[34] There is a broad spectrum of ways for the pilot to pitch the aircraft while staying within the peak angle of attack limit. One example is to make an abrupt pitch step wherein the α quickly peaks then washes out. Another way is to establish a fairly constant pitch rate with α rising to the allowable peak value then holding. Or there can be any number of variations in between these cases.

[35] This is based on a step input into a minimum-bandwidth flight control system where $\omega_{BW} = 2.5$ rad/sec.

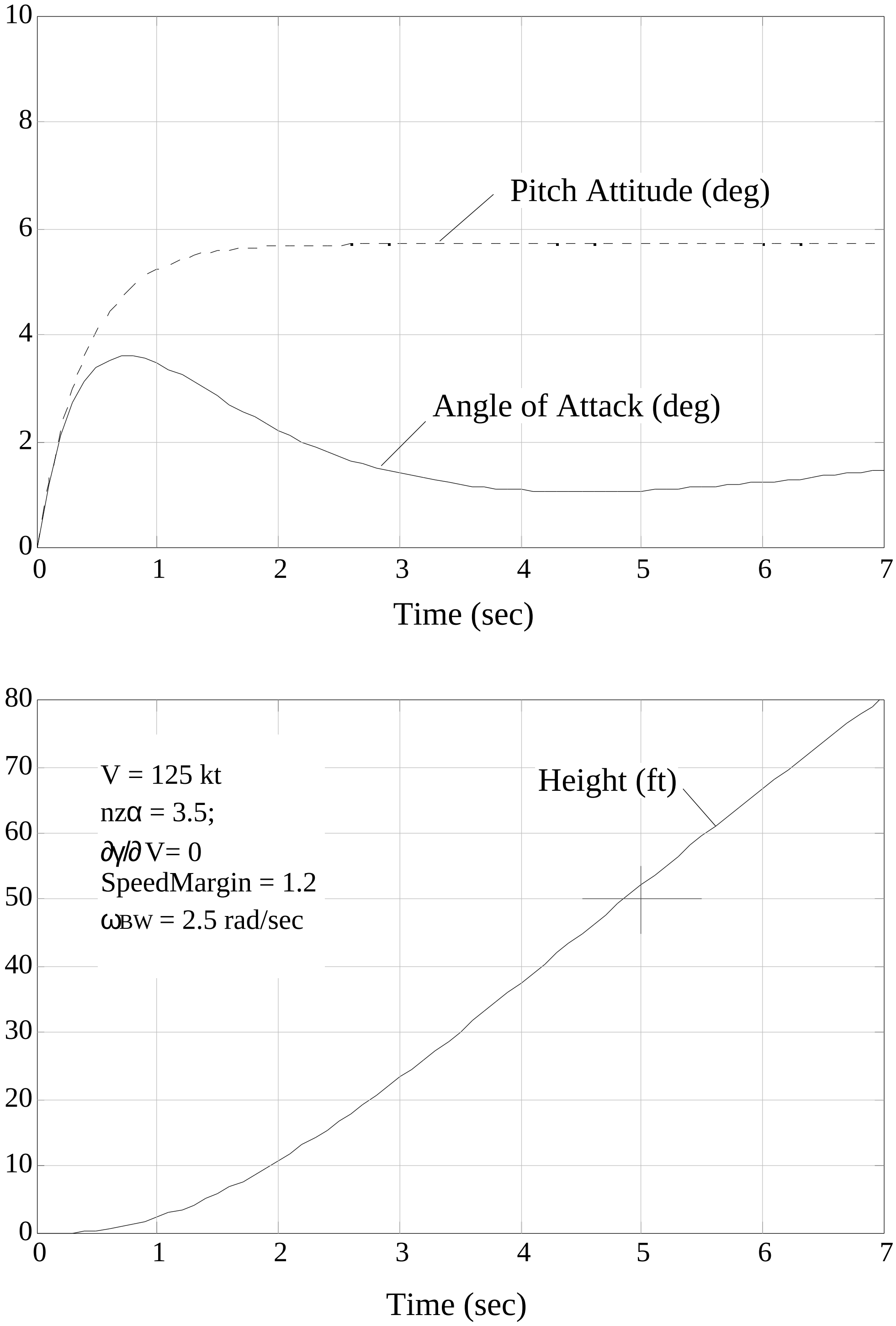

Figure 4-10. Nominal Aircraft Response in Popup Maneuver.

The design parameter $n_{z\alpha}$ is generally considered to be influential in vertical flightpath response. However if its effect on all of the response features is carefully accounted for, the resulting impact on popup maneuver performance is generally-speaking rather weak as Figure 4-11 reflects. In fact, increasing $n_{z\alpha}$ actually increases the time to 50 ft. The minimum value of $n_{z\alpha}$ = 2.5 specified by MIL-F-8785C is indicated. Typical values found in most Navy carrier aircraft at normal approach speeds range from 3.5 to 4 g/rad (refer to Table 2-4).

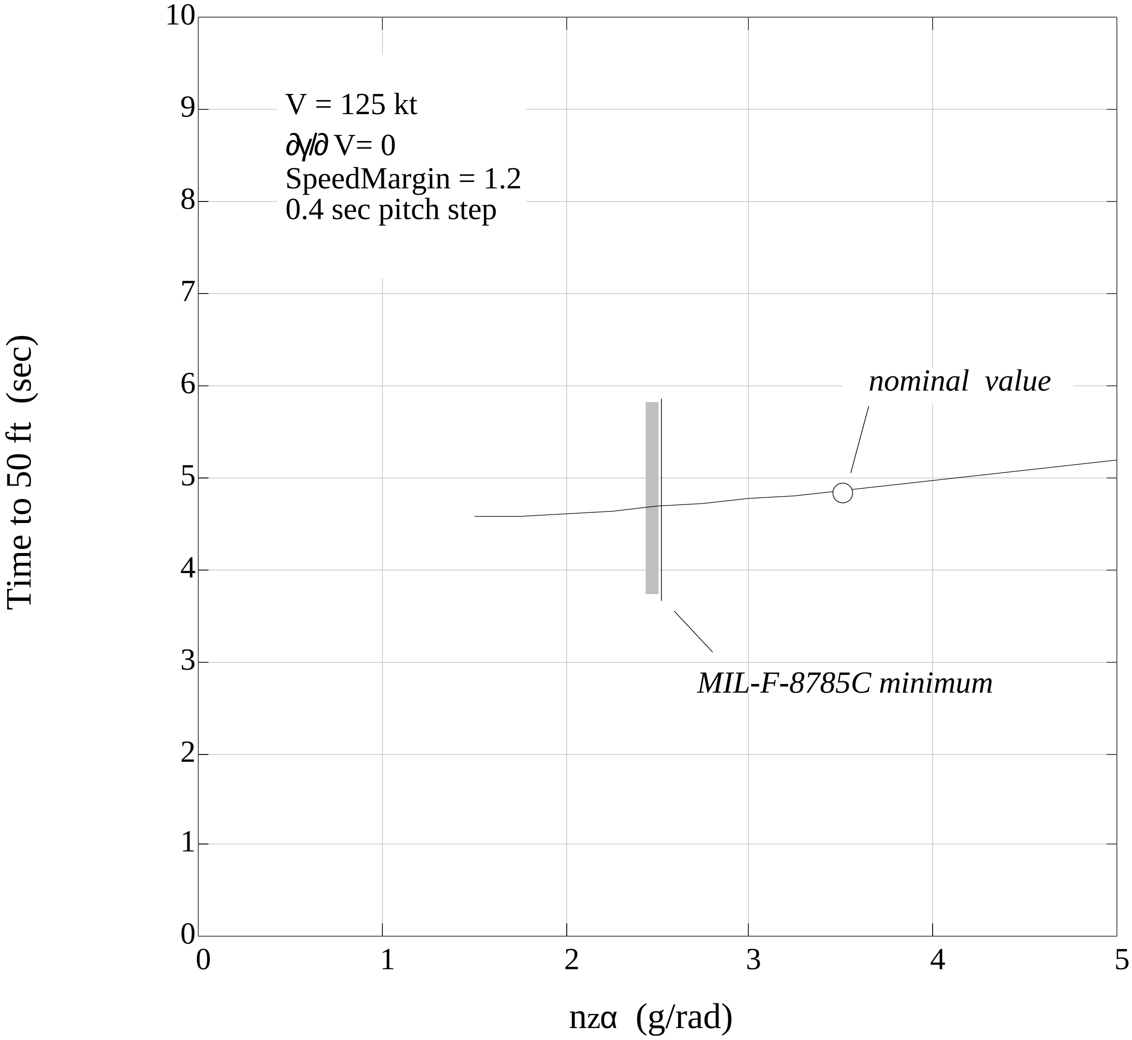

Figure 4-11. Sensitivity of Popup Performance to $n_{z\alpha}$.

Approach speed also affects the time-to-50 ft only slightly, even for a very large range of speeds. As Figure 4-12 shows, higher speeds yield a slightly shorter time-to-50 ft.

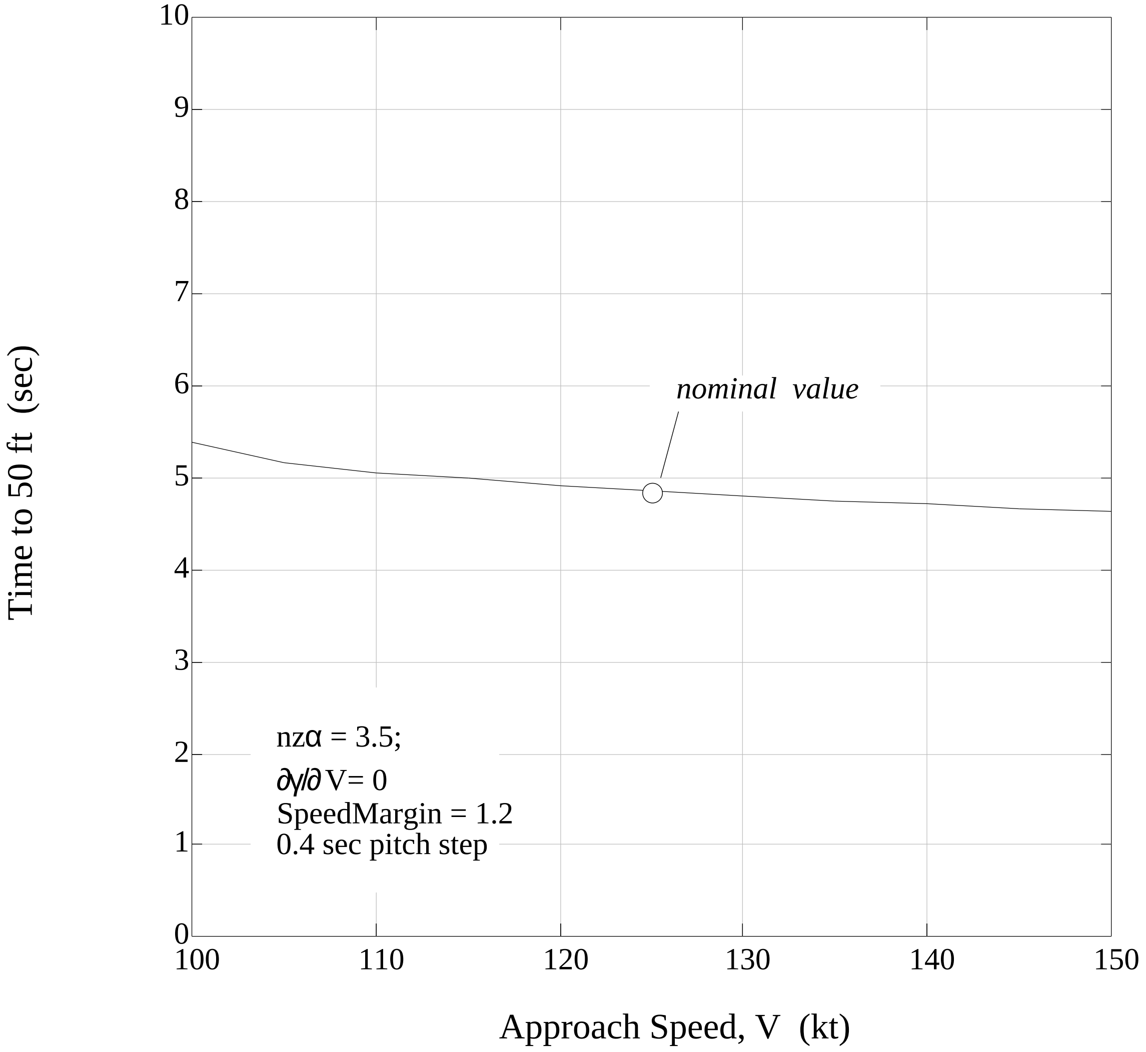

Figure 4-12. Sensitivity of Popup Performance to Approach Speed.

Figure 4-13 shows that the backsidedness parameter also has a rather weak effect on time-to-50 ft. Even the largest permissible $\partial\gamma/\partial V$ of +0.06 (on the backside) does not change the popup maneuver performance much.

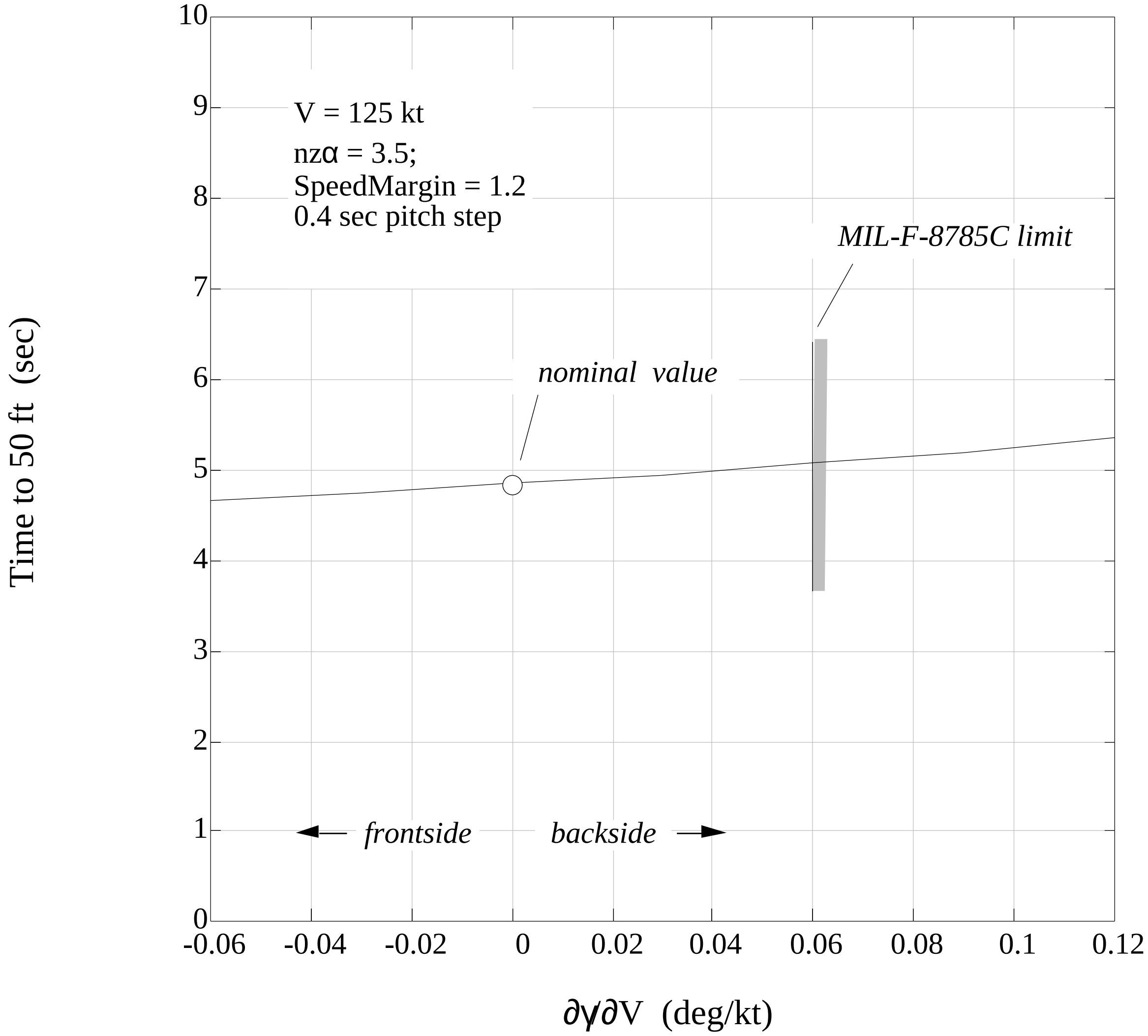

Figure 4-13. Sensitivity of Popup Performance to Backsidedness.

Even the abruptness of the pitch response has surprisingly small effect on the time-to-50 ft. A first-order time constant has been used to vary the profile of the pitchup maneuver. A value of zero for this time constant would correspond to an instantaneous pitch step while larger values would yield more ramp-shaped pitch responses. The limit shown in the plot corresponds to the quickest pitchup obtainable with a minimum bandwidth flight control system as specified by the STI bandwidth criterion (ω_{BW} = 2.5 rad/sec). Longer time constants would be obtainable with increasingly gradual pilot pitch commands. This feature is illustrated further shortly.

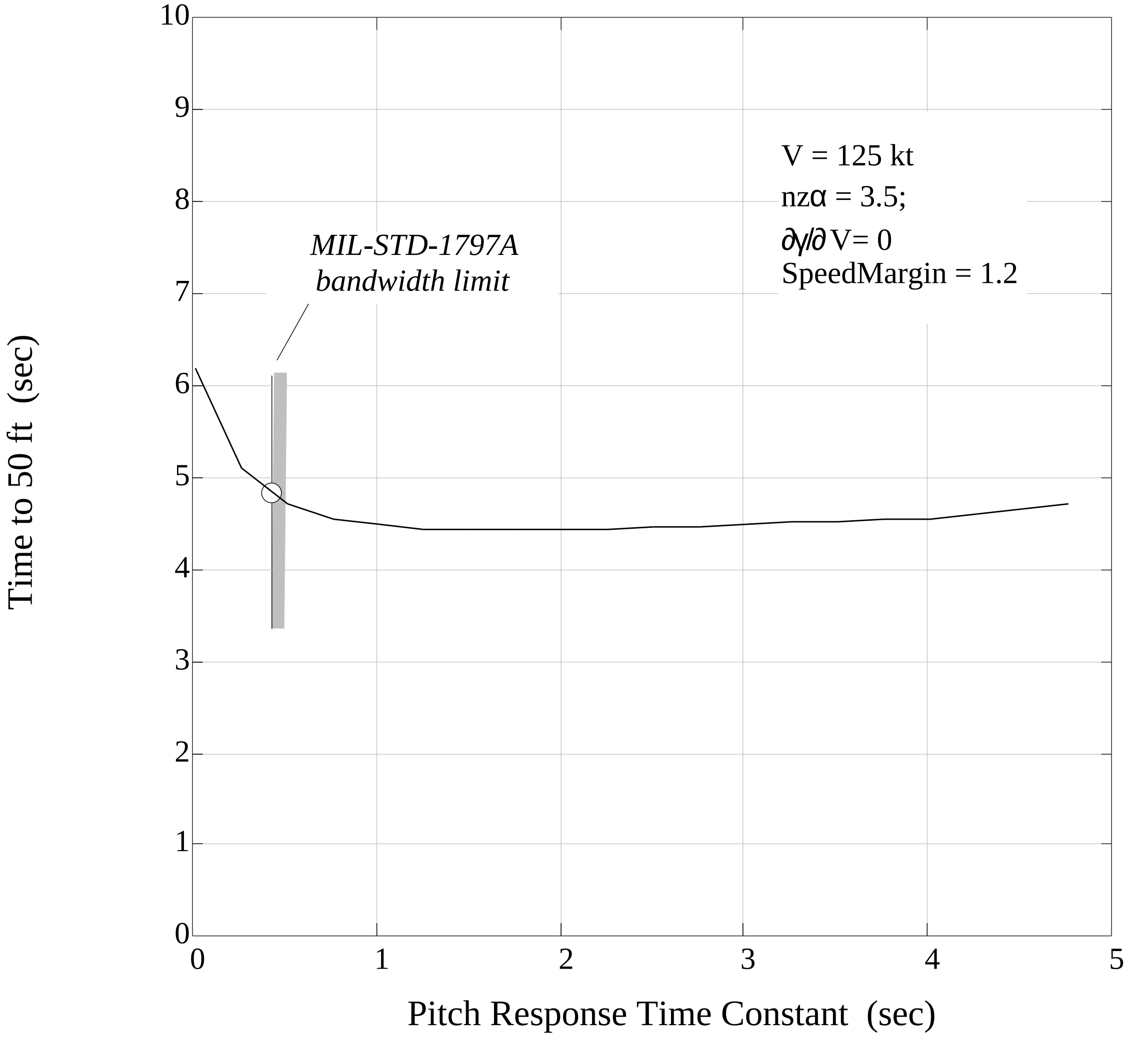

Figure 4-14. Sensitivity of Popup Performance to Pitch Attitude Response.

The one design parameter that does have a large effect on popup maneuver performance is the speed margin, i. e., ratio of approach speed to power-on stall speed. According to Figure 4-15, a speed margin of about 20% is required in order to satisfy the popup maneuver criterion.

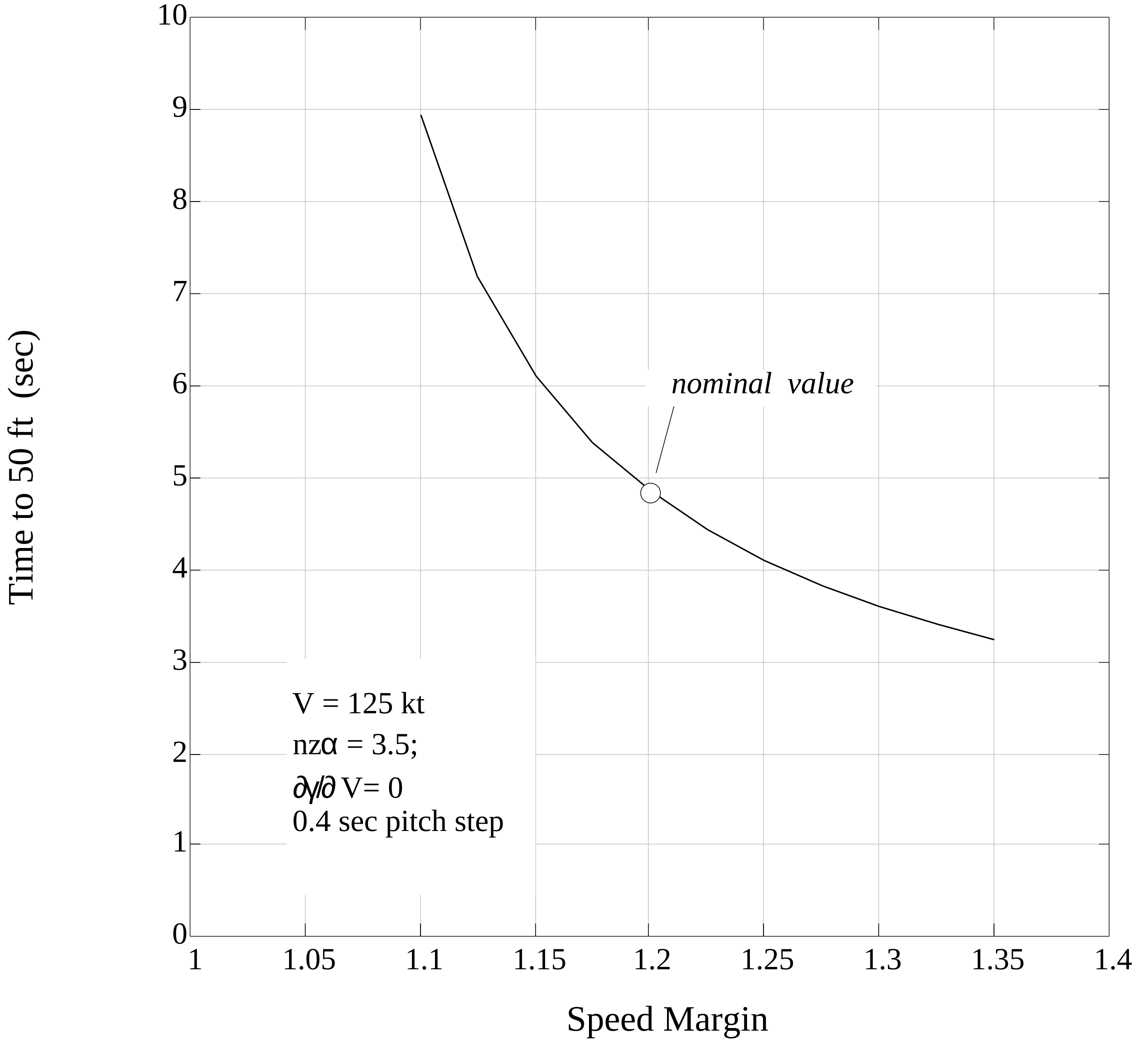

Figure 4-15. Sensitivity of Popup Performance to Margin from Stall.

As indicated previously, the pitch attitude bandwidth does not have much effect. In fact, there is a penalty for pitching up too quickly. In order to obtain a more effective angle-of-attack change, it is advantageous to slow down the pitch maneuver. As shown below, for a very long pitch time constant (5 sec) the maneuver resembles a constant pitch rate. The same peak angle of attack is obtained, but it is sustained rather than decaying. Figure 4-16 shows the comparison the nominal case shown above with the sustained pitch up. Both cases result in about the same time to 50 ft height gain.

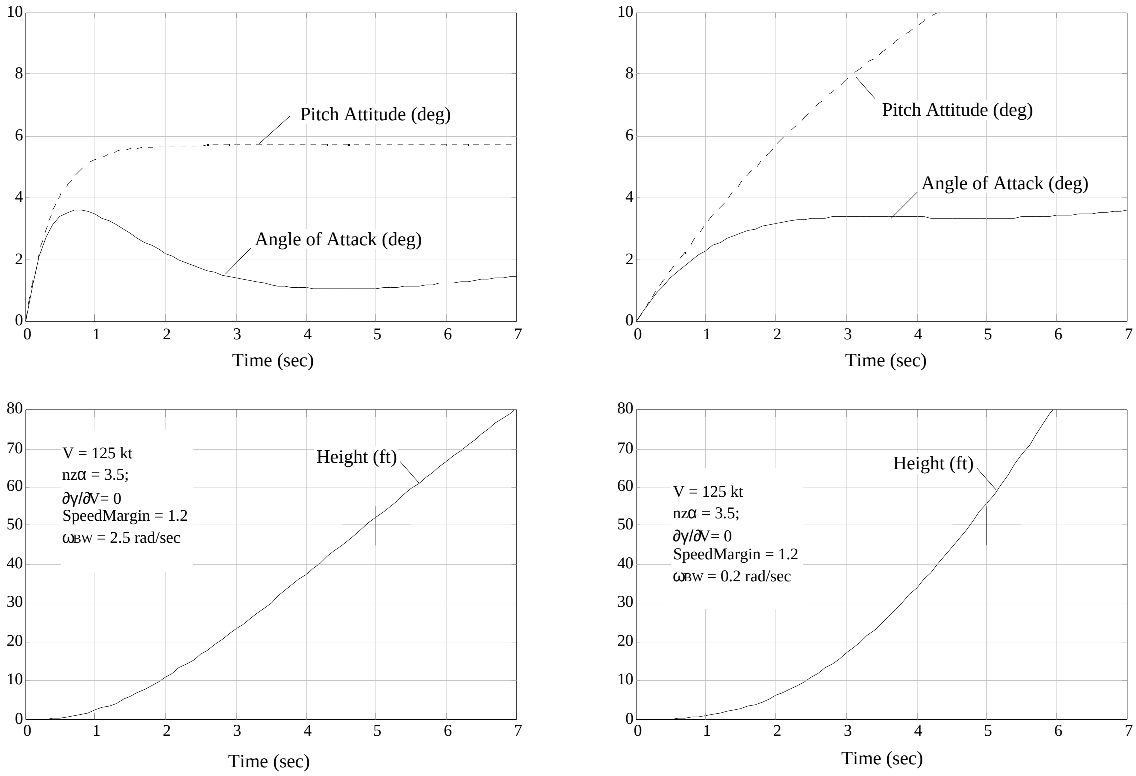

Figure 4-16. Comparison of Popup for Two Diverse Pitch Maneuvers.

In summary, only the stall speed margin appears to have a significant influence on the time to 50 ft. Each of the other parameters can be varied over a wide range without affecting popup maneuver performance by more than a few percent. Given the nominal values of these other parameters, a speed margin of about 20% appears sufficient to guarantee popup maneuver performance.

Variations of the Popup Maneuver

Some variations in the popup maneuver have been mentioned. One concerns the definition of the allowable $\Delta\alpha$, another the terminal condition of the popup.

The angle-of-attack limit defined above is based on the static incremental normal acceleration available. Another definition used during initial flight testing of the popup maneuver based the α limit on the actual Δg available for an abrupt pullup. This resulted in a far smaller amplitude pitchup maneuver for the popup, generally about one-half that based on the static Δg-available.

Another important variation that was used by the Navy for a period of time put an additional constraint on the end of the maneuver. Instead of the 5 sec time-to-50ft limit, the aircraft was given 7 sec to step-up through 50 ft and to pass back through 50 ft. This was a significant additional contstraint because it introduced a closed-loop aspect to the maneuver. The important benefit in terms of outer-loop control is that short-term response of the airframe is crucial to the maneuver and is therefore implicit in the popup criterion. The difficulty, because of the necessary closed-loop pilot actions, is that such a maneuver is more dependent on the technique of an individual pilot than the simple time-to-50ft criterion.

Operation at or Above 1.1 V_{SPA}

The 10% margin above stall speed provides a safety factor in terms both of an angle of attack and of airspeed. If, indeed, the popup maneuver requires a stall-speed margin of about 20%, then the 1.1 V_{SPA} requirement may be unnecessary except for unusual circumstances. If there is a desire to guarantee a specific stall-speed margin, say 20%, then the direct wording of this requirement is better, perhaps, and should replace the popup maneuver in its current form. At the same time, the popup maneuver might be restated to ensure an effective limit on short-term flightpath response.

Visibility over the Nose Upon Intercepting the Glideslope

This requirement directly addresses visual cueing for the pilot. It recognizes that the primary vertical and horizontal flightpath information originates at the deck of the carrier (FLOLS and dropline). The geometry specified implies a downward field of view limit over the nose. The visibility requirement to see the stern at an altitude of 600 ft while flying level implies that the visibility over the nose be equal to the approach angle of attack plus 4.8°. For example, if the F-18 uses a true angle of attack of 8.1 deg, then over-the-nose visibility must be at least 12.9° below the FRL.

Inner-loop cueing is not covered in this requirement, however. It is crucial for the pilot to have both pitch attitude and thrust cues in order to effectively control outer-loop states. Pitch attitude is usually implicit in the requirement for visibility over the nose. There can be a problem if there is no distinct nose reference, though.[36] The other crucial inner-loop cue is thrust level. Pilots ordinarily depend upon engine sound, but in some aircraft such as the A-7 and F-14, the sound level is well insulated from the pilot. HUD display of thrust level can provide a good substitute, particularly if the commanded level is shown. This has the benefit of eliminating the problem of thrust lag in making throttle adjustments.

4.2.3 Summary of $V_{PA_{min}}$ Criteria

The $V_{PA_{min}}$ criteria effectively set the following features:

(i) Engine thrust lag less than 0.52 sec (depending upon interpretation)
(ii) Upward and downward steady-state flightpath angle correction of at least 7°
(iii)Margin from power-on stall speed of about 20% (10% explicitly)
(iv)Downward field-of-view adequate for the final approach leg
(v) Various pitch-attitude response requirements of 8785C

Notably absent from this list are:
(i) Short-term flightpath response (such as $T_{\theta 2}$)
(ii) Quality of the flightpath response (such as speed damping, $T_{\theta 1}$)
(iii)Engine thrust-level cueing

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[36] This might be the case if the downward field of view were taken to an extreme, say, 90° from the horizontal.

4.3 Computation of the "Last Significant Glideslope Correction"

4.3.1 General

It is crucial to understand how the aircraft characteristics examined previously fit into the total context of the final approach to the carrier. The following simple time-domain analysis accomplishes this by showing how basic aircraft response affects successful completion of the carrier landing task. Factors include those relating to the pilot, aircraft, task geometry, and LSO.

This analysis considers a "final significant glideslope correction," i. e., a discrete maneuver. It has already been demonstrated that any discrete pilot correction requires a time interval, the length of which depends on how aggressively the pilot operates. One can also interpret this time interval as a distance-traveled if multiplied by the average velocity. Thus, it is possible to work backward from the ship in order to compute the point in space at which the pilot must initiate the final correction maneuver.

4.3.2 Math Model Description

One can use the following basic system math model to explore the relationship between pilot-vehicle and flight task. It is composed of a single loop around altitude with three open-loop response modes: a free-s (representing the integration of vertical velocity), an airframe lag, T_1 (representing the effective heave response given pilot coordination of pitch and thrust), and a control lag, T_2 (representing some combination of pitch and thrust control lag).

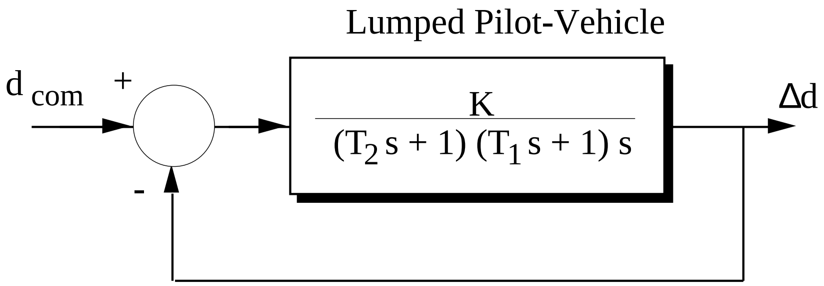

Figure 4-17. Simplified Representation of Pilot-Vehicle System.

$K \approx k \cdot V$ (approximate "crossover frequency" or "bandwidth")
$T_1 \approx -1/Z_w$ (heave damping, i. e., limit of vertical response)
$T_2 \approx T_{eng}$ and/or $1/\omega_{BW}$ or $0.7/\omega_{sp}$ (effective control response)

Using the above math model framework, one can first explore the effect of pilot aggressiveness by simply varying the gain, K. The resulting set of height responses to step commands is shown in Figure 4-18.

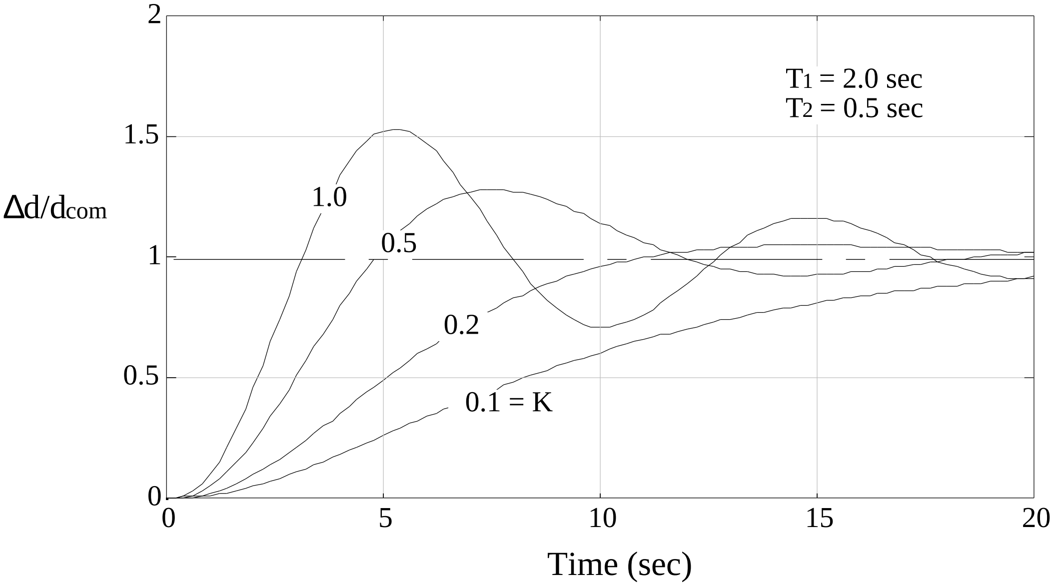

Figure 4-18. Normalized Height Response as Pilot Aggressiveness Varied.

Note that as aggressiveness is increased, rise time decreases and overshoot increases. The following table contains solutions for the three gain selections shown above:

Table 4-1.
Glideslope Range and Response Parameters for Example.

Gain, K	T_{90}	Overshoot	Δ Range
0.1 ft/sec/ft	19.3 sec	none	indeterminate
0.2	9.0	0.044	1521 ft
0.5	4.4	0.27	746
1.0	2.9	0.53	495

where

$$\Delta \text{ Range} = V_c \cdot T_{90}$$

$$= 169 \text{ ft/sec} \cdot T_{90}$$

The rise-time-to-90% of the command is assumed to be the metric reflecting how quickly the correction is made.

The overshoot is assumed to represent the general precision of the correction. This is a convenient device which preserves linearity in the analytical solution. At the same time it is a realistic means for representing the main feature which opposes increasingly aggressive control.

Figure 4-19 shows the scheme for portraying a glideslope correction in terms of basic time-domain features.

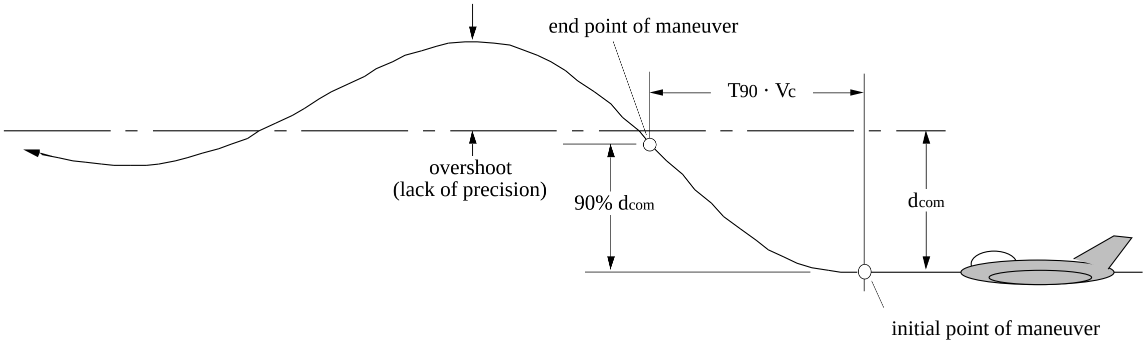

Figure 4-19. Scheme for Measuring Performance of Glideslope Correction.

The main feature of interest is the precision. This is the proportion of the overshoot to d_{com} and is considered relative to the distance over which the correction is made, $T_{90} \cdot V_C$. As shown previously, increasing pilot aggressiveness will shorten the distance to make the correction but it will also worsen the overshoot.

Now consider this analysis approach in order to examine the glideslope correction capability for a nominal pilot-aircraft system in the context of typical carrier approach geometry.

4.3.3 Analysis Results for a Nominal Pilot-Aircraft Combination

The family of time-response curves can next be applied to the carrier approach scenario with the following interpretations on time-of-response and precision-of-response. First, consider the basic task assumptions used for this analysis:

(i) The last significant correction should be completed no closer to the touchdown point than *at-the-ramp* ("AR"), i. e., about 600 ft from the nominal touchdown point (which is the #3 wire).

(ii) The vertical flightpath precision should be related to the ability to catch a given wire. Since the wire spacing is about 40 ft and the nominal glideslope angle is 4°, the equivalent vertical flightpath precision would be about 33 in.

(iii) The rise-time-to-90%, T_{90}, is the time to do the task. Using the closure speed with the ship, V_C, this establishes the point at which the last significant correction is begun. Thus the corresponding range would be 600' plus $T_{90} \cdot V_C$.

(iv) This scheme assumes that the pilot uses an optimal coordination of thrust and pitch in order to minimize AOA upsets while maximizing flightpath response. This is reflected by the basic math model form used.

(v) Also limit the maximum correction rate-of-descent to correspond to the LSO's perception of too much or too little glideslope excursion rate, i. e., 0.2° /sec.

From the above assumptions a boundary can be computed which represents the locus of points in the vertical plane from which the aircraft will reach an on-glideslope condition at the ramp (OK GS and OK rate-of-descent). This allows for the LSO to make a final judgement of the approach and for the aircraft to continue on a trajectory to the desired arresting wire. Inherent in the method is that pilot aggressiveness is left to vary in order to make whatever tradeoff is necessary between response quickness and precision.

Some aspects are neglected in the interest of simplicity. First, the effects of atmospheric disturbances (burble, gusts) on precision are assumed to be smaller than the maneuver-induced upset. This is reasonable for at least the larger-amplitude corrections. Second, the effect of AOA corrections is ignored, but this is consistent with use of a coordinated pitch/thrust control strategy. Finally, no nonlinear effects are taken into account. This will be found acceptable upon seeing that relatively small measures of control power are actually involved whether at long or short ranges.

Figure 4-20 shows the locus of points in the vertical plane which bound the ability of the pilot-vehicle to achieve successful trajectory conditions upon reaching the "AR" point of the approach. The LSO-based glideslope and range positions are labeled.

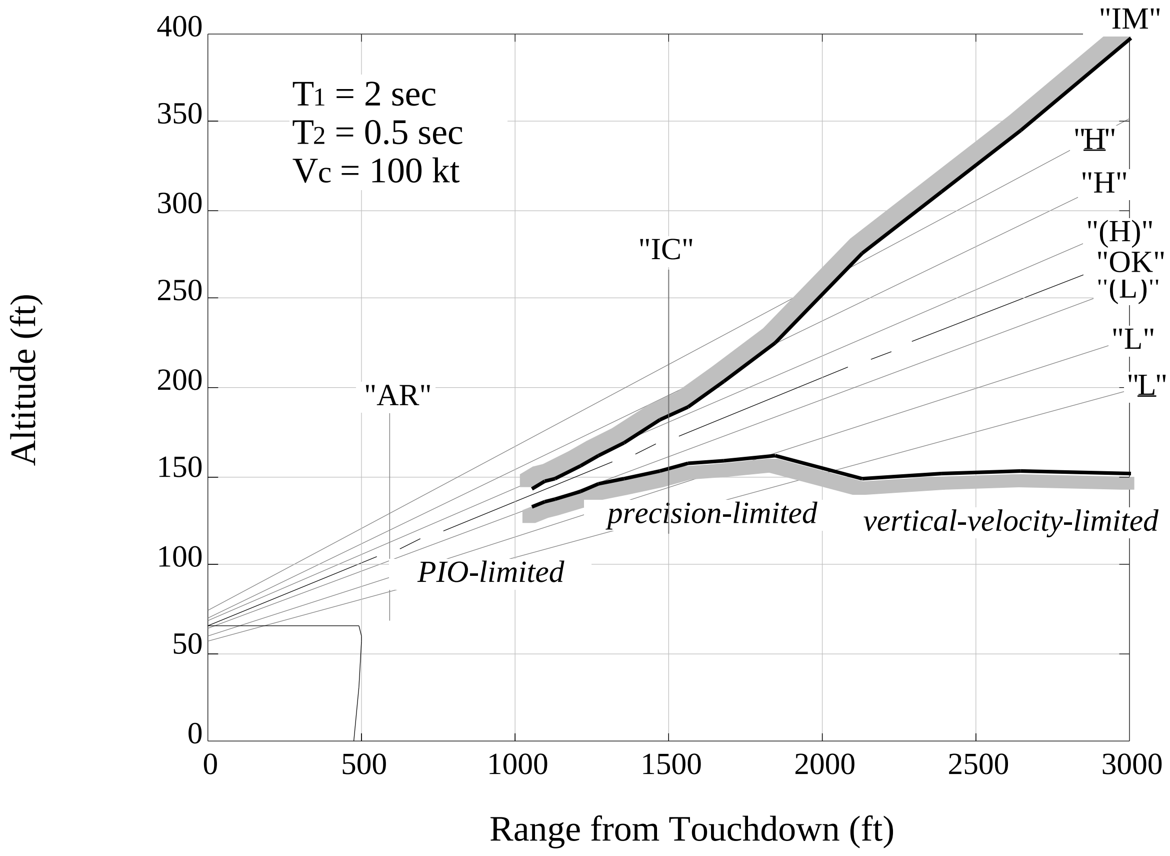

Figure 4-20. Envelope of Permissible Correction Points for Nominal Aircraft Response.

Figure 4-21 presents the same information, but with the maximum allowable glideslope correction boundaries plotted in terms of FLOLS angular error.

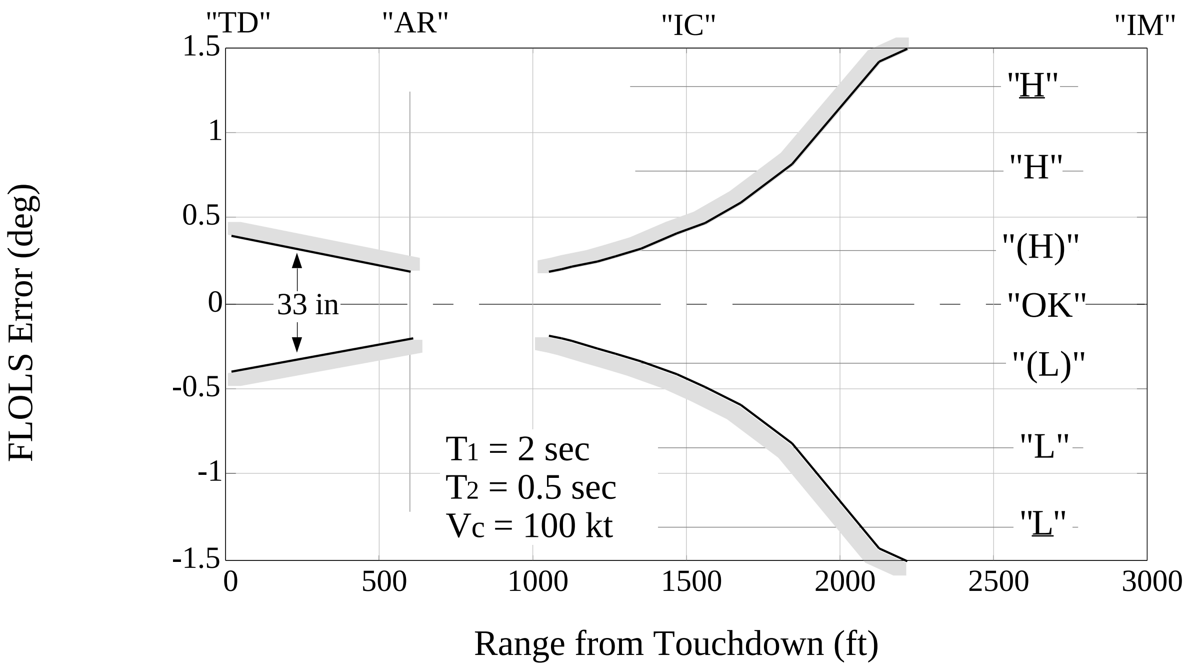

Figure 4-21. Envelope of Permissible Correction Points in Terms of FLOLS Angular Error.

Note that for ranges beyond about 2100 ft (0.35 nm) the pilot-aircraft system can achieve an "OK-AR" (on glideslope at the ramp) from any point ranging from "L" (very low, -1.3°) to "H" (very high, +1.3°). From 1800 ft this also can be accomplished, but only from "L" (0.8° low) to "H" (0.8° high). Increasingly smaller corrections are possible as the final correction range is moved closer to the ship. At about 1000 ft any correction approaching the necessary precision would result in a flightpath PIO (the closed-loop damping ratio is divergent).

Figure 4-22 shows the corresponding maximum vertical velocity excursions for maneuvers which begin at the glideslope deviation boundaries plotted above in Figure 4-21. The segments on the far left (labeled NERD and TMRD) reflect the ± 0.2° /sec glideslope rate of change limit found in the LSO standard in Table 2-1.

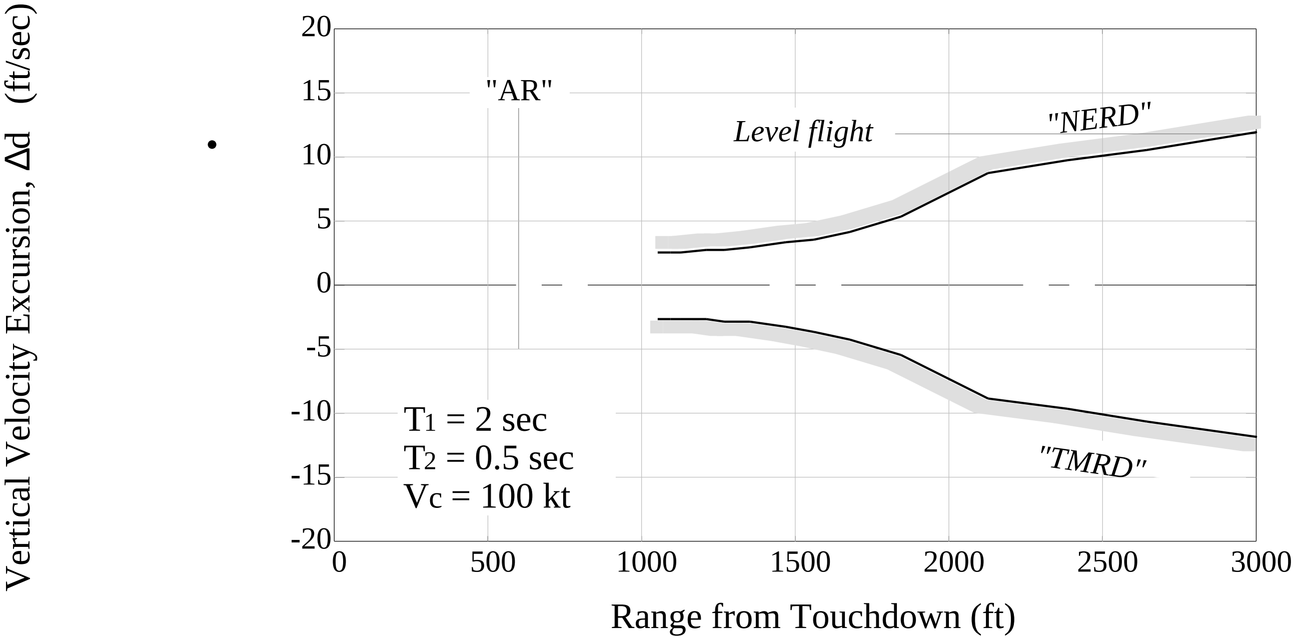

Figure 4-22. Envelope of Peak Vertical Velocity Excursion for a Permissible Correction.

Similarly, Figure 4-23 shows the corresponding maximum control authority used as a function of the range. Recall that a coordinated pitch and thrust correction is used. Further, based on earlier analyses, the relative amounts of each control are approximately numerically equal for Δ T/W and Δ θ in radians. Note that the amount of control authority that the pilot uses is fairly small.

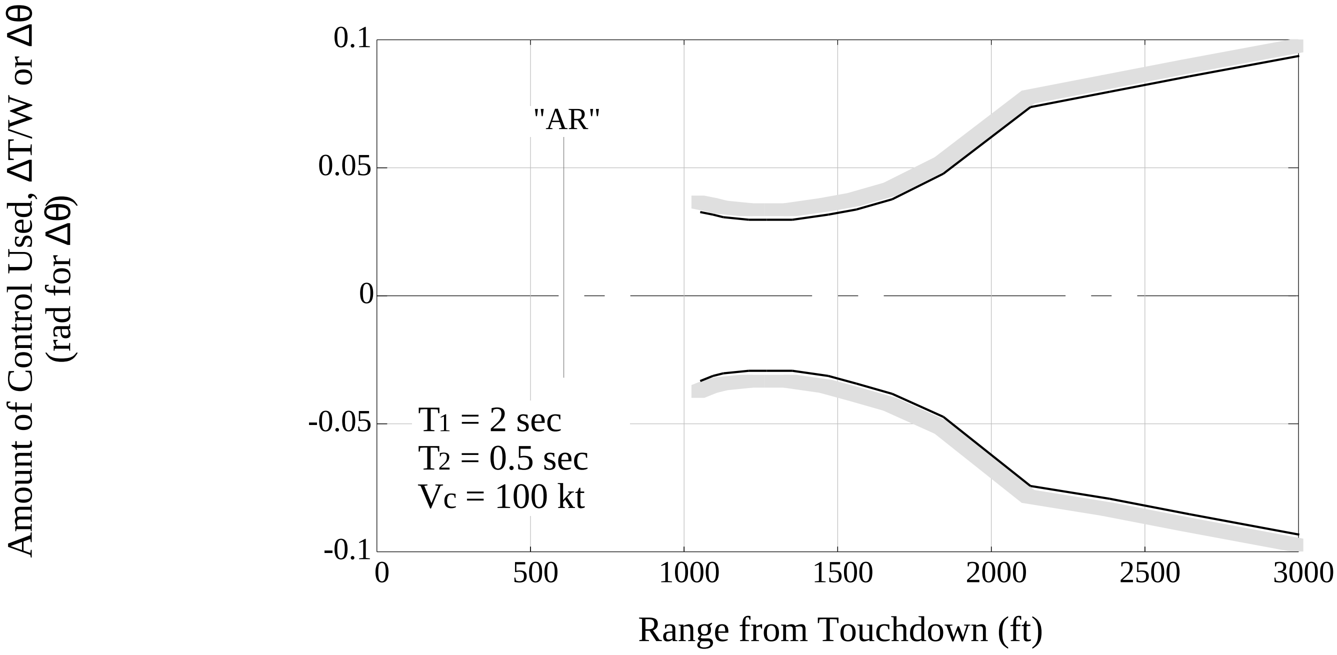

Figure 4-23. Envelope of Control-Required for Permissible Correction.

The plot showing maximum control can also be used to establish required amounts of flightpath control power.[37] This example indicates that about 6° Δ θ and 0.1 Δ T/W would be adequate for a correction starting at the "IM" point. Also, a less aggressive correction starting further out requires substantially more control power than a more aggressive one from a closer range.

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[37] This plot also has implications for *direct lift control* (DLC). The same scale can be interpreted as the approximate peak Δ g required of a DLC.

Figure 4-24 completes the set of glideslope-correction boundary plots for the nominal set of conditions by showing the closed-loop damping ratio as a function of range. This indicates how oscillatory is the final glideslope correction as the maneuver is started at increasingly closer ranges from touchdown. The desirable range for closed-loop damping ratio is about 0.6 to 0.7. The residual oscillation becomes excessive below 0.3, that is a PIO. However, recall that the basic math model provides a consistent level of precision for the first overshoot, i. e., 33 inches vertically.

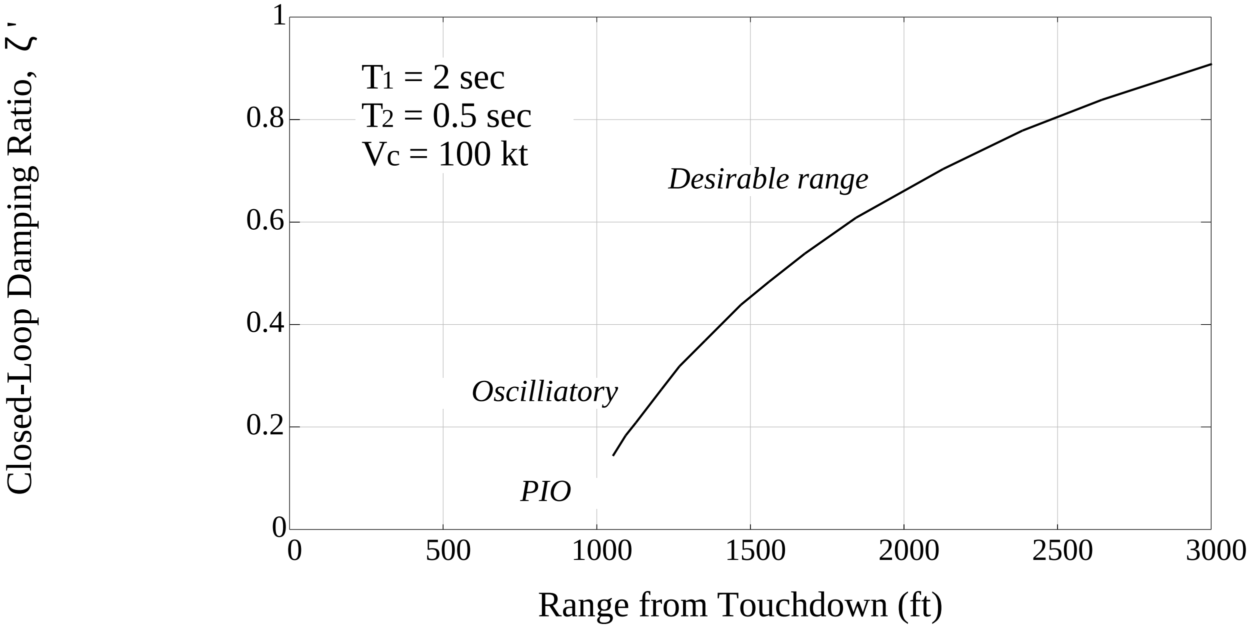

Figure 4-24. Closed-Loop Damping Ratio for the Terminal GS Correction.

4.3.4 Effect of Outer-Loop Control Features on Task Performance

The analysis approach described above and illustrated for a nominal set of conditions is next used to explore the effects of lumped outer-loop control features, T_1, and T_2. The parameter T_1 represents the airframe effective lag and is most closely associated with $T_{\theta 2}$. T_2, the effective control lag, would usually represent the effective pitch-attitude lag as determined by the FCS, but could also include engine lag in some cases.

Effect of T_1, Airframe-Related Time Constant

If the airframe lag, T_1, is varied the impact on glideslope control is profound as Figure 4-25 shows. The last significant glideslope correction must be made progressively further out as T_1 increases. This follows the fact that the scale length of the response, $\lambda_{GS} = T_1 \cdot V_C$, gets correspondingly longer. For example, a correction from "H" must begin at about 1800 ft if T_1 is 2 sec, and 2500 ft for 3 sec.

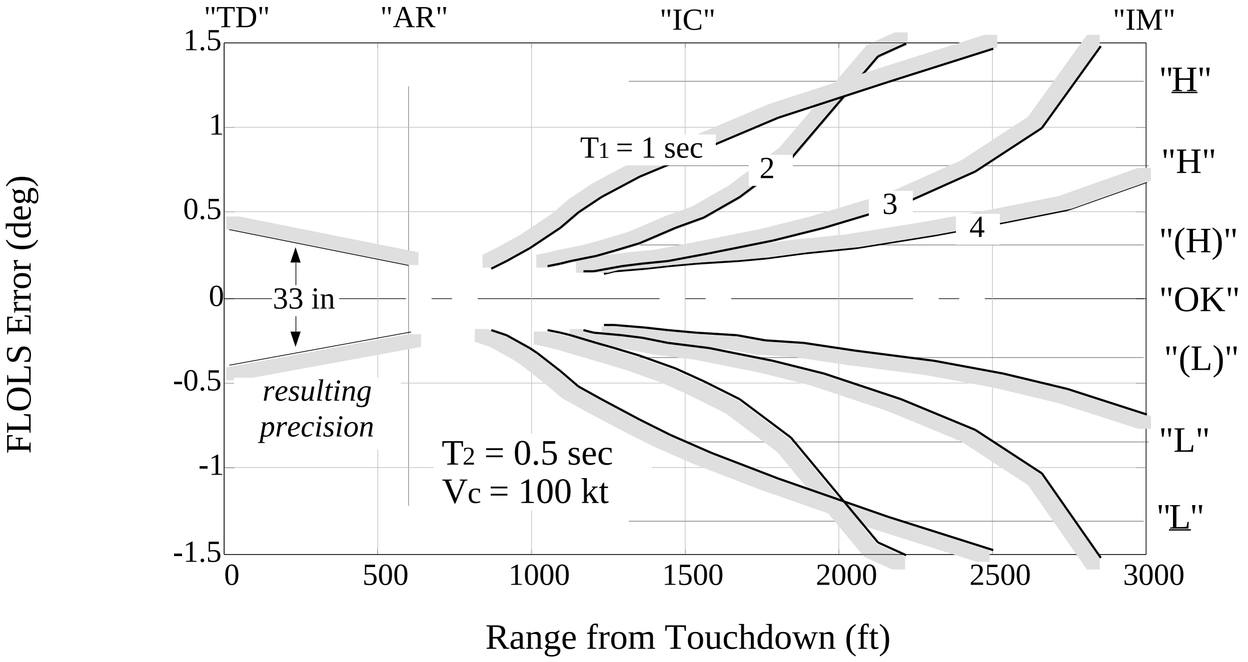

Figure 4-25. Effect of Airframe Lag, T_1, on Permissible Glideslope-Correction Boundary.

Figure 4-26 and 4-27 show, for T_1 variation, the corresponding plots of vertical velocity excursion and amount of control used. In both of these plots and increasing T_1 diminishes substantially the amplitudes, even for corrections started at a long range from the ship.

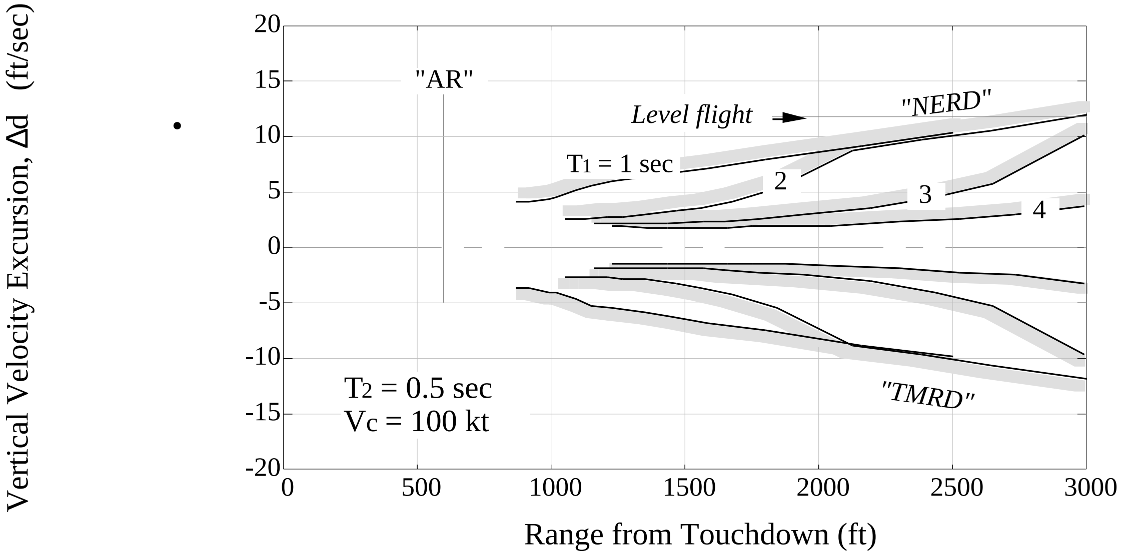

Figure 4-26. Effect of Airframe Lag, T_1, on Vertical Velocity Excursion.

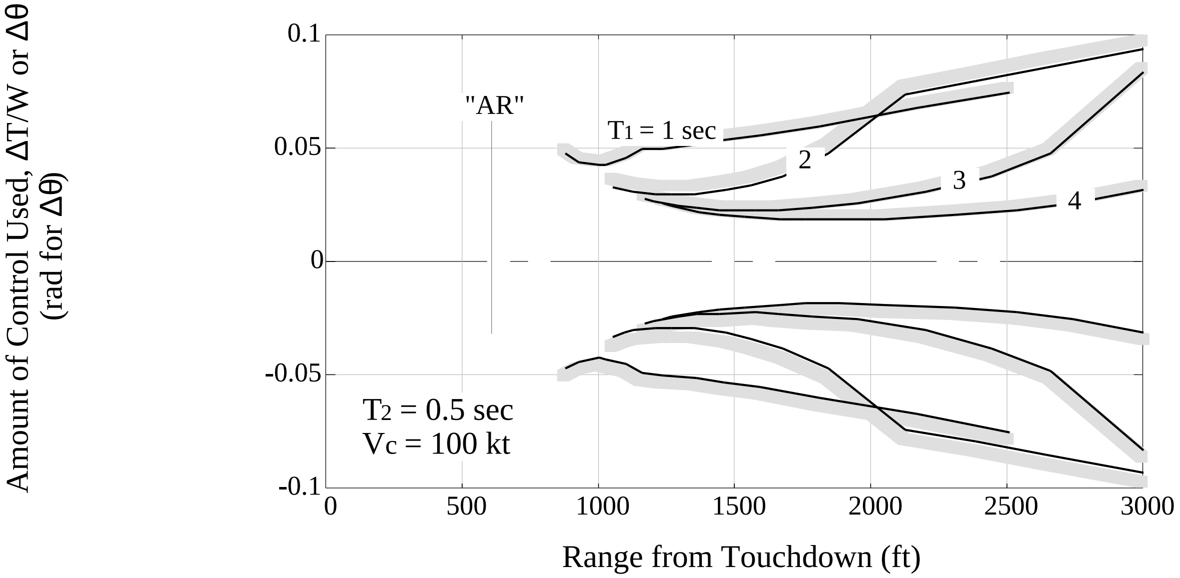

Figure 4-27. Effect of Airframe Lag, T_1, on Control Authority Required.

Effect of T_2, Control-Related Time Constant

The next set of figures show how the effective control lag, T_2, affects the *last significant glideslope correction.* The nominal airframe lag, T_1, is 2 sec and the closure speed is 100 kt. A close inspection of these boundaries indicates that the effect of T_2 is very nearly equivalent to that of T_1. This is not surprising in view of their respective roles in the basic math model. The similarity of results also is indicated in the vertical-velocity and control authority boundaries shown in Figures 4-29 and 4-30.

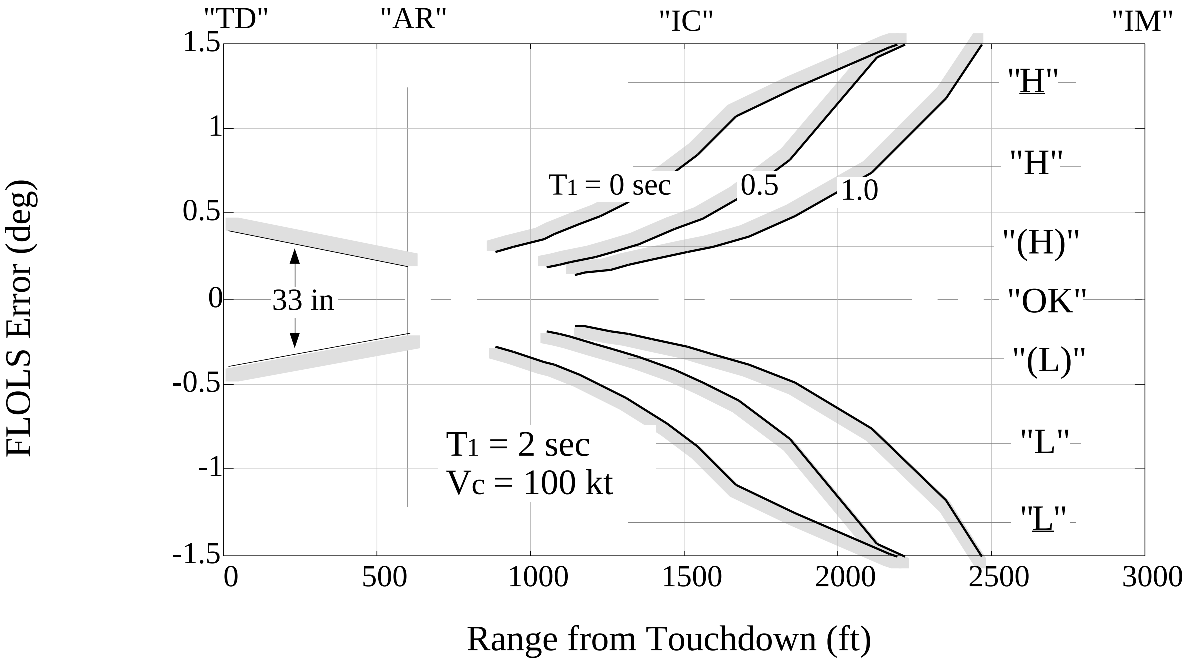

Figure 4-28. Effect of Control Lag, T_2, on Boundary of Permissible Glideslope Correction.

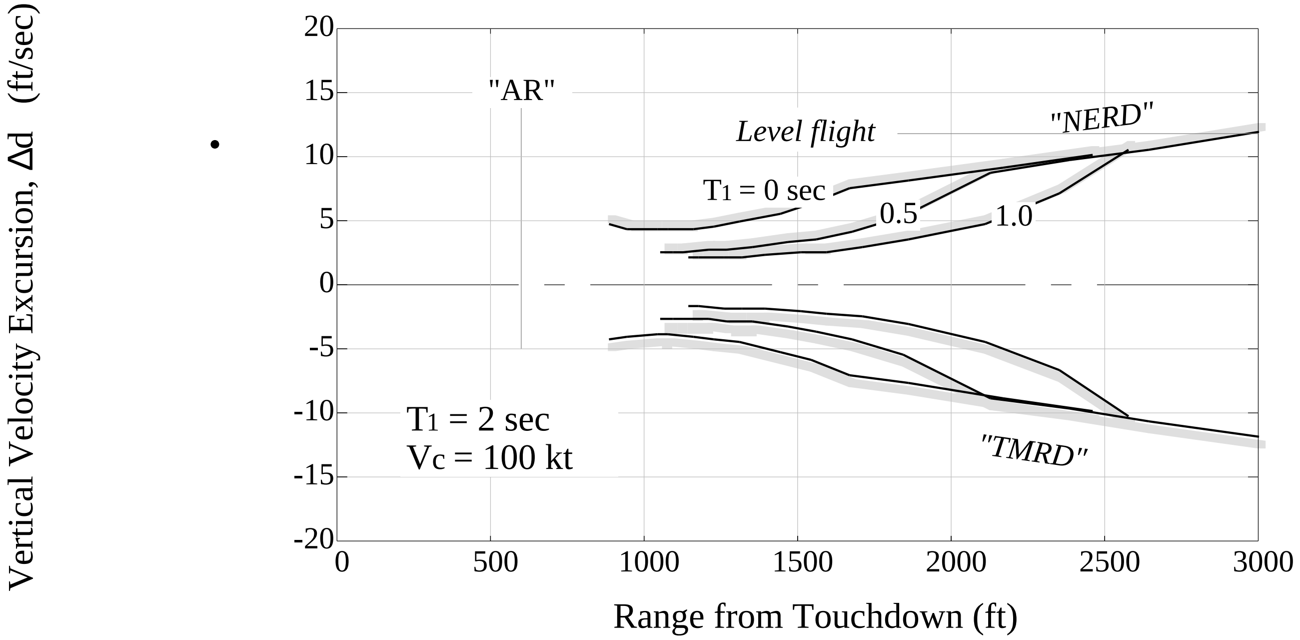

Figure 4-29. Effect of Control Lag, T_2, on Vertical Velocity Excursion.

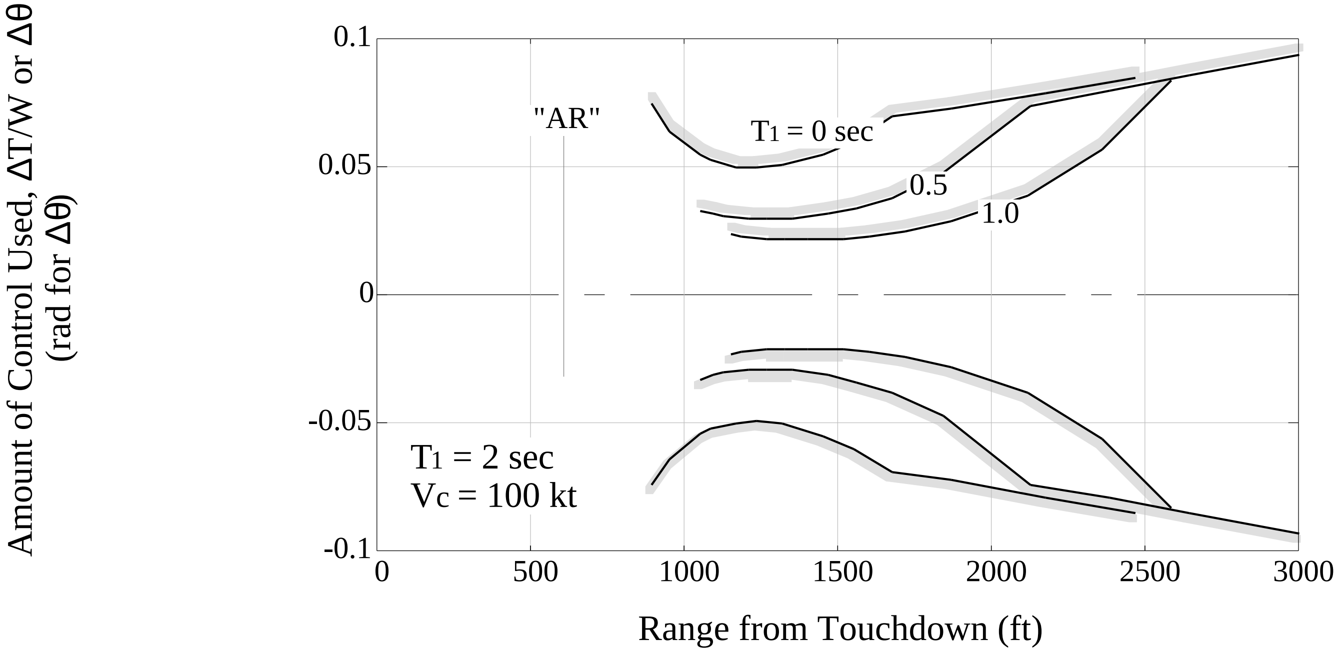

Figure 4-30. Effect of Control Lag, T_2, on Control Authority Required.

4.3.5 Summary of Last-Significant-GS-Correction Analysis

The product of the dominant flightpath-response time constant and the closure speed is, indeed, one chief determinant in achieving an acceptable terminal glideslope condition. Direct addition of the control lag provides a more comprehensive list of effects as both T_1 and T_2 impact glideslope control in about the same way. And finally, closure speed simply scales distance for the correction to the time constants involved. These effects also were demonstrated by the simulator results reported in Reference 3.

The rule-of-thumb for how far the pilot can be from the “AR” point (600' from touchdown) in order to start a final correction from “H” or “L” (the edge of the FLOLS vertical beam) is about 3 times the product of (T_1+T_2) and closure speed. For a correction from “(H)” or “(L)” this factor is about 1.8. The distance for correction therefore can be based on a simple scale length principle where the scale length:

$$\lambda_{GS} = (T_1 + T_2) \cdot V_C$$

Thus, a correction from a high condition requires $3\lambda_{GS}$ and from a slightly high condition, $1.8\lambda_{GS}$.

On the other hand, the air-distance required to make a path correction is invariant with speed and only a function of wing loading, lift-curve slope (aspect ratio), and air density:

$\lambda_{GS}(T_1) = T_1 \cdot V_C \approx V \cdot T_{\theta_2} \approx (2 \cdot W/S) / (\rho \cdot g \cdot C_{L_\alpha})$, a constant for a given airframe.

In contrast, the distance required to make a stabilized speed correction is a very strong function of the airspeed, i. e., proportional to the fourth power of speed.

$$V \cdot T_{\theta_1} \approx \rho \, C_{L_\alpha} V^4 / (4g \, W/S)$$

The size of corrections computed for these terminal maneuvers is substantially smaller than that involved in the popup maneuver. This coupled with the fact that the popup maneuver is largely independent of the short-term flightpath response $(1/T_{\theta_2})$ further suggests that there should be an additional requirement for short-term flightpath response. The control response component is already restricted to something less than about 0.5 sec, whether engine or pitch attitude response.

4.4 Inner-Loop Control Lag Influence on Flightpath Response

The quality of flightpath response is basic to the success of a carrier landing. The previous analysis shows this using a simple closed-loop math model. It also shows the nearly-proportional relative effect of the airframe, T_1, compared to the inner-loop control, T_2. The next step is to examine T_2 in terms of the importance of its two components, pitch attitude and thrust, but a more complex analysis approach is needed.

The procedure to determine the roles of pitch attitude lag and thrust lag makes the following assumptions:

(i) The pilot uses an optimal coordination of pitch and thrust in order to minimize the AOA excursion in the medium term.

(ii) Step commands of pitch and thrust begin simultaneously.

(iii) The metric of short-term response is the overall rise-time-to 63% of the flightpath angle.

(iv) The effective lags for pitch and thrust are varied independently.

Figure 4-31 shows the results of this procedure for the F-14 airframe. If the pitch and thrust lags are both zero, the effective rise-time is about 2.3 sec, slightly faster than the basic value of $T_{\theta 2}$. If the pitch lag is increased but the engine lag held zero, then the effective rise time is about equal to $T_{\theta 2}$ plus the effective pitch lag. However, if pitch lag is zero and only engine lag is increased, the effective rise time does not change much. For non-zero combinations of the two lags a similar trend prevails. The effective short-term response potential is a direct additive function of pitch lag, but thrust lag contributes only as a second-order effect.

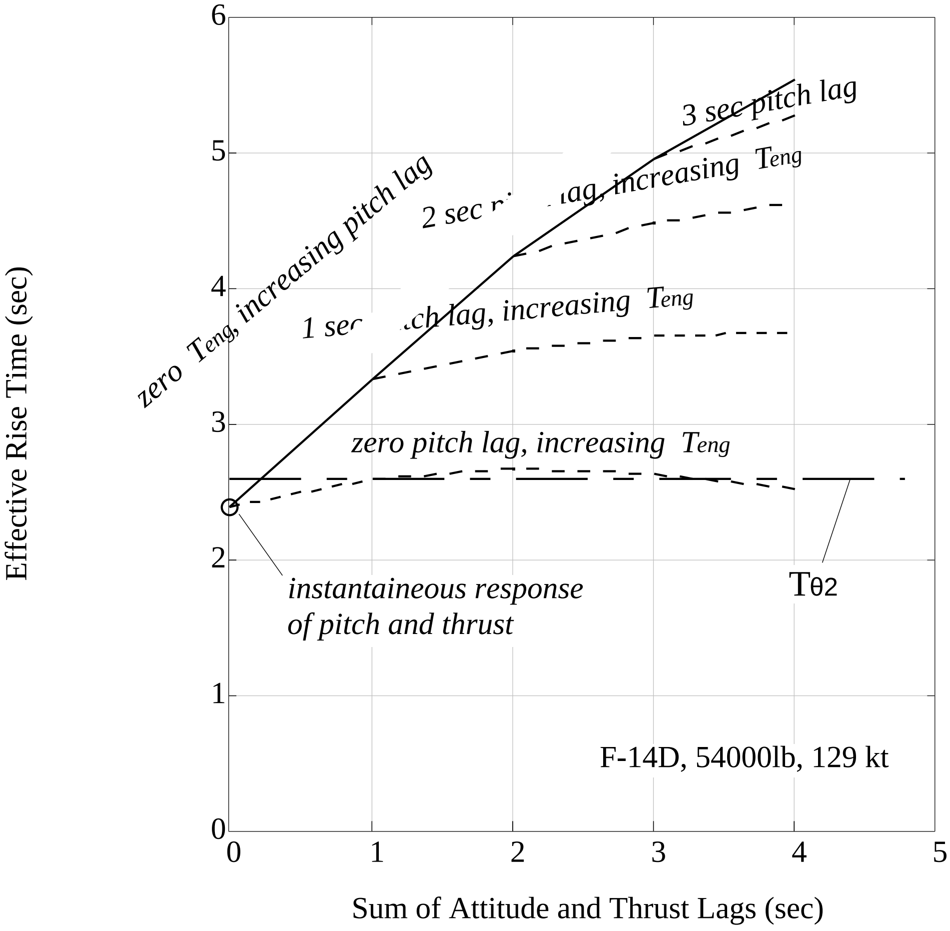

Figure 4-31. Relative Importance of Inner-Loop Lags for F-14.

Figure 4-32 shows the same analysis for the F-4, an aircraft having a fairly large thrust inclination. The results are very nearly the same. The effect of pitch attitude lag is greater than that of the engine. Finally, a similar result is shown for the T-45 in Figure 4-33.

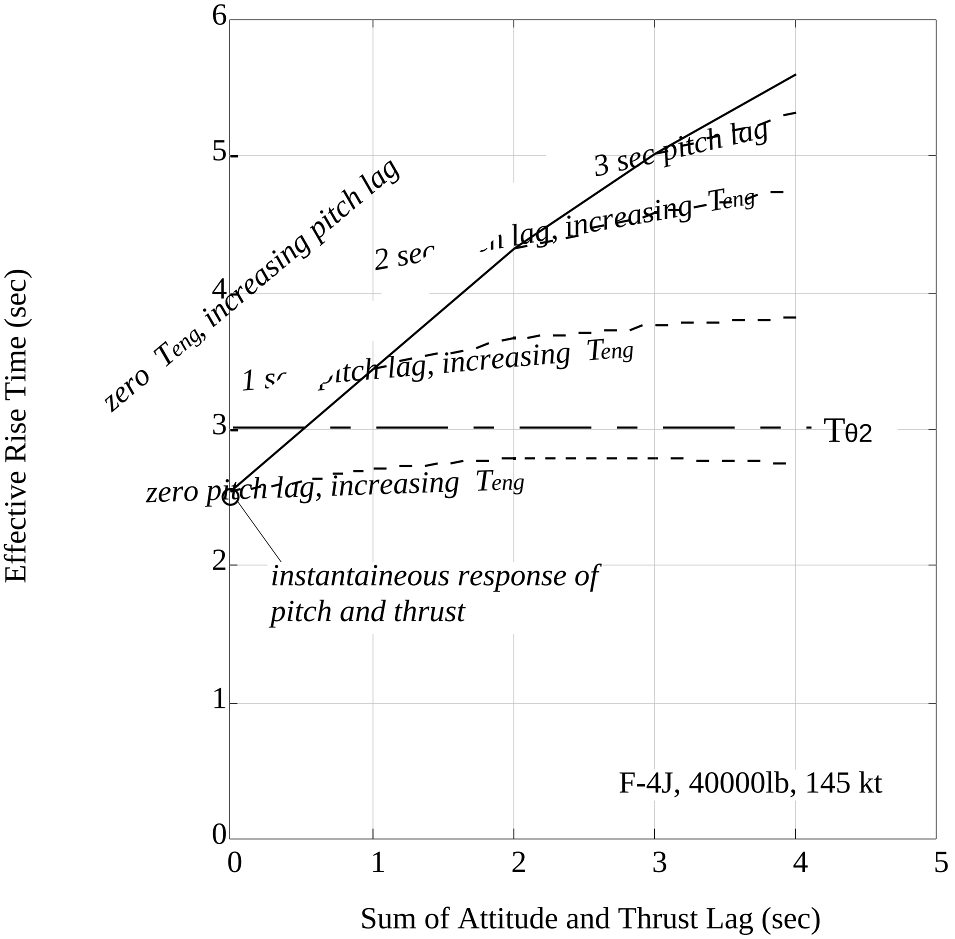

Figure 4-32. Relative Importance of Inner-Loop Lags for F-4.

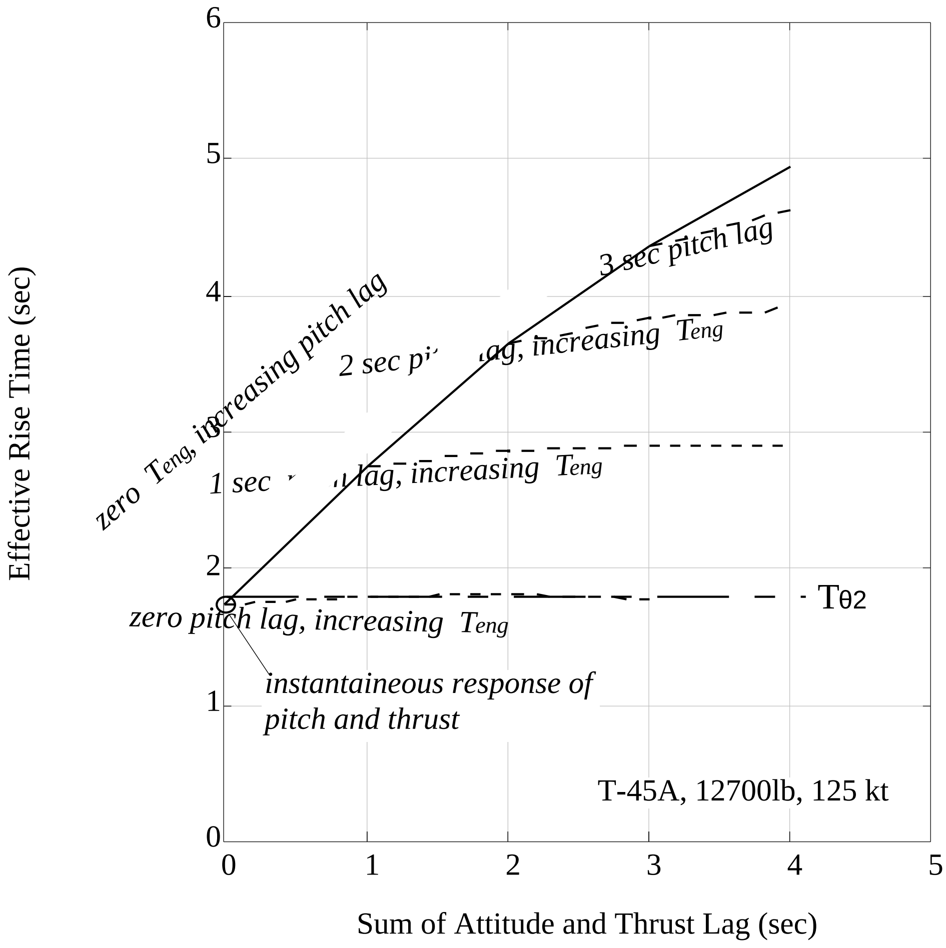

Figure 4-33. Relative Importance of Inner-Loop Lags for T-45.

4.5 Effect of Engine Lag on Control of Thrust

The previous analysis shows that thrust lag does not limit directly the short-term glideslope response-potential. Therefore, one needs to explore the effect of thrust lag from a different point of view.

Informal interviews were conducted with pilots who have operated aircraft with slow-responding engines (high-bypass-ratio turbofans). The main complaint appeared to be in simply making thrust adjustments, a basic inner-loop task. As described, the pilot has difficulty in predicting the eventual thrust level following the initial throttle change when made without reference to engine gages. There is simply no reliable initial cue which correlates with the steady-state thrust. The problem is most acute when restoring thrust from a near-idle condition. (Recall from Section 2 that thrust lags are greatest at low power settings.)

A review of the outer-loop control structures for the likely control strategies indicates that thrust control is really an inner-loop control function, similar to pitch attitude control. Further, the essential response features of thrust are that (i) it is a proportional control (the steady-state thrust level follows throttle position) and (ii) the status is usually monitored aurally, at least during the latter stages of the approach where use of cockpit gauges is inadvisable.

Thus the maximum thrust lag should be a function of inner-loop control activity. The thrust lag, T_{eng}, should influence how quickly the pilot can make a simple thrust adjustment using only the feedback of engine noise.[38] One analytical method which has been demonstrated valid for similar inner-loop applications is the Hess Structural Pilot Model.

Hess Structural Pilot Model

R. Hess has developed a theoretical approach to predict the effect of various design features on aircraft handing qualities (Reference 67). He has applied it successfully to the effects of motion cueing (Reference 68), and has succeeded in correlating several experiments in which pilot ratings were collected for a wide range of system types (Reference 69). This includes the broad class investigated by J. McDonnell in Reference

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[38] One assumes that engine noise is a direct function of the actual thrust level as opposed to the commanded thrust level.

70. Hess recently applied the procedure to an outer-loop task, namely, the landing flare for conventional aircraft (Reference 71).

The Hess method applied here is primarily successful in predicting the boundary between Level-1 and Level-2 flying qualities, i. e., where Cooper-Harper ratings (Reference 72) transition from acceptable to unacceptable. One accomplishes this by computing a Handling Qualities Sensitivity Function (HQSF) which, if it exceeds unity, indicates Level-2 flying qualities (Cooper-Harper rating greater than 3.5).

In the process of this study, the Hess approach was applied to the analysis of both inner-loop and outer-loop control situations in order to study the effect of many parameters. Only the inner-loop thrust control case is presented here in order to minimize the use of sophisticated analysis approaches and also because the method has not been used extensively for outer-loop applications. Nevertheless there is considerable potential for future use of this method to explore the effects on flying qualities of specific system parameters.

Application of Hess Method to the Thrust Lag Problem

The inner-loop management of thrust can be modeled according to the block diagram shown in Figure 4-34. The main system parameters are only the effective thrust lag, T_{eng}, and the pilot's effective delay, τ_o.[39]

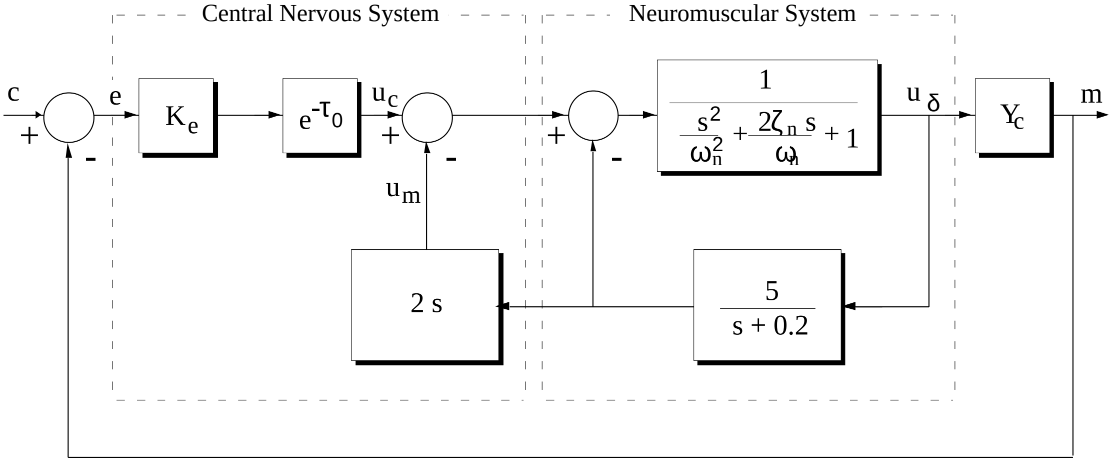

Figure 4-34. Hess Structural Pilot Model.

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[39] The block diagram shown here is set up specifically for a lag-type controlled element.

If the effective delay is assumed to be 0.15 sec, we can compute the maximum pilot crossover frequency at which the Hess HQSF exceeds unity. Figure 4-35 shows this for three crossover frequencies (levels of pilot aggressiveness) and an engine lag of 0.3 sec. A crossplot of the results yields a crossover of 2.44 rad/sec as the maximum aggressiveness for Level-1 flying qualities.

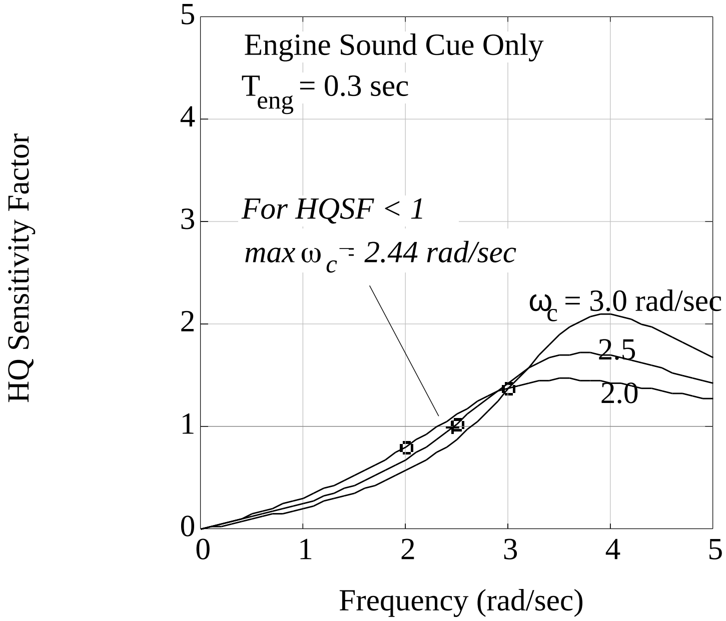

Figure 4-35. Sample of HQ Sensitivity Factor Solutions.

This process is repeated for several values of T_{eng} in order to map the Level-1 flying qualities boundary (HQSF = 1). The results are presented in Figure 4-36 in terms of the maximum pilot aggressiveness as a function of engine lag.

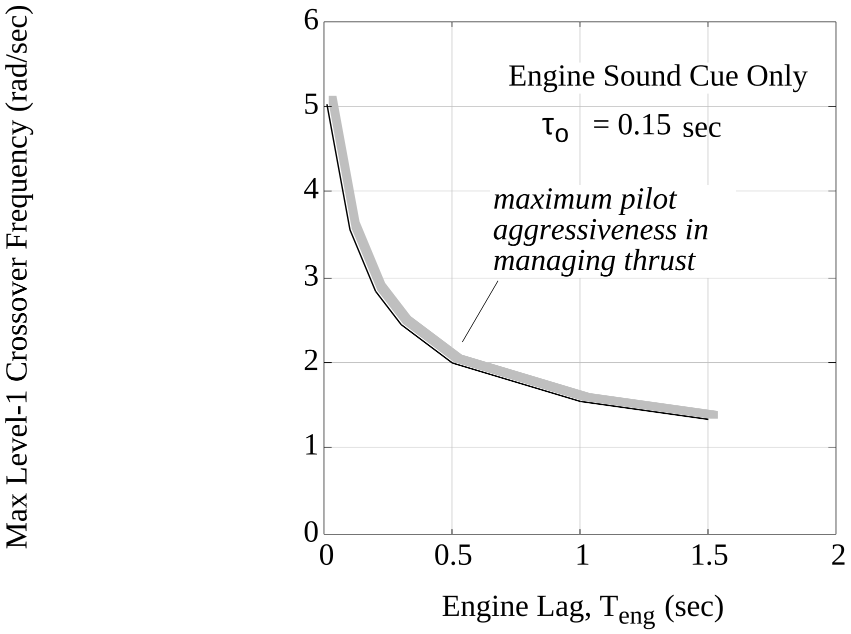

Figure 4-36. Max Acceptable Crossover Frequency vs Engine Lag.

To put this result into perspective, there is a rule-of-thumb that any supporting (inner-) loop must have a bandwidth approximately three times that required by the primary (or outer loop). If the primary loop requires a bandwidth of 1 rad/sec (a time constant of about 1 sec) then the supporting control must have a bandwidth of about 3 rad/sec (or a time constant of about 0.3 sec). In this case, a T_{eng} of 0.5 sec could permit the pilot to adjust thrust at 2 rad/sec with acceptable workload. This would support outer loop activity at about 0.7 rad/sec. Not coincidentally, this is about the level of aggressiveness typically seen in the phase-plane portraits of the previous approach data (Section 4.1).

The requirement for 0.5 sec lag in this type of control has been established in two rather diverse standards. First, recall that the Navy V_{PA} criteria require an engine lag of about 0.52 sec. Second, one can observe that in the current rotorcraft handling qualities specification, ADS-33C (Reference 73), the bandwidth requirement for an attitude-command system is 2 rad/sec. The response type matches that of a throttle system and the 2 rad/sec value would correspond to the engine lag requirement cited above.[40]

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[40] This is perhaps too loose an analogy since the definition of bandwidth for an attitude-command system in ADS-33C is based on a second-order system (at least 180° of phase rolloff) and the engine more closely resembles a first-order system.

The Navy approach speed criterion which now limits thrust lag appears to have some justification. However, given the need for the pilot to make quick thrust adjustments without head-down reference, this may be a matter which properly should be addressed in the flying qualities specifications. Further, this issue may be particularly acute for turbofan engine installations in a number of critical flight phases, including airborne refueling and close-formation flight.

5. CONCLUSIONS AND RECOMMENDATIONS

The analytical study of outer-loop control factors for carrier aircraft has led to several conclusions regarding aircraft design and testing processes. These conclusions are summarized below, and recommendations are given for additional analysis and experimentation.

5.1 Conclusions Based on Analysis Results

The paragraphs below summarize, with a brief discussion, the important results of this study. General conclusions are followed by several more specific ones.

5.1.1 General

- **A candidate list of outer-loop control factors serves as a starting point.**

Section 3 of this report presents, without quantification, a systematic list of outer-loop control factors based on a general assessment of the carrier approach task and existing control criteria. This is a useful tool for examining the effectiveness of existing criteria, identifying weaknesses, and recommending modifications and additional criteria.

- **Outer-loop control factors presently are covered only partially.**

The combination of existing flying qualities requirements and the Navy approach-speed criteria presently provides a degree of coverage of outer-loop control factors for carrier aircraft. However, there is no systematic identification of those factors and corresponding design criteria. The MIL-STD-1797A flying qualities specification furnishes a general framework but fails to back it up quantitatively, particularly for outer-loop features of the carrier landing task. Overall, the existing requirements address many outer-loop control factors, but not directly and explicitly. Specific cases are detailed in several of the following items.

- **The carrier-landing task lacks quantitative definition.**

Presently there is no quantitative definition of the carrier landing task that describes the minimum requirements for pilot *aggressiveness*, *amplitude* of maneuvers, *precision* of terminal conditions, and *settling* of corrections. The only explicit task feature is the *duration* of the approach given by the distance from the roll-out into the final leg and the closure speed with the ship. LSO performance criteria furnish useful background information but are not sufficient for an engineering definition of the task.

The main benefit of a comprehensive task definition is that one could compute directly most of the necessary for outer-loop control factors. This would promote a degree of consistency among the individual control factors and economy when imposing them as design requirements. The failure to have a comprehensive task definition forces reliance on subjective assessment of task performance and of the effectiveness of design requirements.

- **Pilot technique for the carrier landing task is defined only subjectively.**

Pilot technique or control strategy for the carrier landing is not well understood or defined in clear quantitative terms. The classical "backside" technique attributed to Navy use, if rigidly interpreted, severely limits pilot aggressiveness in controlling flightpath. There is some danger that this might lead to inappropriate design assumptions. Careful measurement and analysis of data obtained from flight could yield an accurate assessment of the technique, or variety of techniques, that Navy carrier pilots actually use. In turn, this would be an important component in the quantification of task performance.

- **Pitch-constrained equations offer the analyst a powerful tool.**

Pitch-attitude-constrained equations of motion provide a simple but powerful analytical tool for examining outer-loop stability and control features.

(i) They embrace fundamental, easily-estimated, parameters.
(ii) They permit inner-loop control features to be partitioned and treated separately.
(iii) They emphasize the strong, fundamental influence of lift and drag on flightpath and airspeed dynamics.

This tool is particularly useful for examining the bridge between the disciplines of *stability and control* and of *performance,* at least where the effects of nonlinearities do not prevail. Although, even where there are significant nonlinearities, say in lift or drag, many of the basic pitch-constrained principles remain valid and useful.

- **The Navy's use of AOA as a speed reference has special implications.**

Given that pitch attitude is actively regulated by the pilot, angle-of-attack response mathematically is the complement of flightpath angle. This implies that any constraint on flightpath control features also governs AOA control features. Attitude-constrained equations show directly that dynamics of angle-of-attack and flightpath are closely related. Further, this relationship effectively minimizes the number of system parameters necessary to describe dynamic response of the outer-loop control states involved in the carrier approach.

5.1.2 Specific Conclusions

• Current Navy approach-speed criteria are necessary but not sufficient.

Each component of the Navy approach speed criteria implies certain constraints on the outer-loop control, but these constraints are not sufficiently comprehensive to cover all aspects crucial to performing the carrier landing task.

Features which are covered include:

- Flightpath control-power upward, applicable to the waveoff task
- Flightpath control-power upward and downward, applicable to the approach task
- Engine thrust lag for the nominal flightpath-angle power setting
- Pitch attitude response lag, control power, and manipulator characteristics
- Margin from power-on stall (implicit in popup and explicit in $1.1V_{S_{PA}}$ req’t)
- Visibility of deck-centered glideslope and lineup cues (downward field of view)

Features which are not covered include:

- Short-term flightpath response
- Engine thrust lag for off-nominal power settings
- Quality of flightpath response (such as speed damping effects)
- Engine thrust-level cueing in the absence of a HUD

Other observations made:

- Popup maneuver defines "safe" pitchup amplitude
- Criteria assume a "conventional" non powered-lift airplane

• Flying-qualities specifications mainly address inner-loop pitch response.

The Navy approach-speed criteria requirement for compliance with MIL-F-8785C affects mainly inner-loop control of pitch attitude due to the traditional emphasis of aircraft flying qualities. Outer-loop control benefits are minor and indirect. MIL-STD-1797A furnishes a more systematic framework that includes outer-loop control but does not contain well-supported outer-loop backup data. Its main strength also is inner-loop pitch control criteria. Neither specification addresses inner-loop control of thrust.

• The thrust acceleration-response requirement covers both engine lag and flightpath control power but is subject to misinterpretation.

The criterion requiring not more than 1.2 sec rise-time-to-90% for a ± 3.86 ft/sec^2 longitudinal acceleration command can limit two important control features. First, it can indirectly provide for a level of flightpath control authority equivalent to about ± 7° incremental flightpath angle. Second, the rise time, if expressed as an equivalent first-order lag, limit the maximum thrust lag to 0.52 sec. Both are key factors for outer-loop control, but there is a potential difficulty.

The favorable control constraints described above are really based on interpreting the command as the incremental *thrust-to-weight ratio* rather than *longitudinal acceleration.* The latter quantity does not approach a commanded value, but instead washes out as the speed-damping takes effect. Use of the longitudinal acceleration state can result in unclear and unfavorable interpretations of the effective thrust lag and flightpath control power.

• Primary outer-loop design parameters have been identified.

The lowest-common-denominator set of design parameters for any pitch-induced flightpath maneuver, including the popup, consists of:

- Airspeed, V
- $n_{z\alpha}$
- Margin from stall, V/V_{SPA}
- Pitchup abruptness (time-constant of pitch command)
- Backsidedness, $\partial \gamma / \partial V$

This set recognizes certain interdependencies among the response factors (including $T_{\theta 1}$, $T_{\theta 2}$, and T_{h1}) defined by pitch-constrained equations of motion.

The main effects of individual parameters are:

$n_{z\alpha}$	in combination with airspeed, a key element in flightpath response modes
V	primary determinant of time-available to make corrections
$\partial \gamma / \partial V$	strong modifier of basic speed damping, speed-stability a secondary role
V/V_{SPA}	affects the available maneuvering amplitude using pitch control
Δ T/W margins (±)	permit sustained changes in flightpath, i. e., control authority

ω_{BW} or ω_{sp}	effective pitch control short-term response
T_{eng}	effective thrust control short-term response

(There are few corresponding parameters for the horizontal-plane outer-loop response characteristics. The main ones of interest would be inner-loop response in the roll axis and the turn coordination quality.)

- **The 5 sec-to-50 ft popup maneuver mainly reflects stall margin.**

The popup maneuver 5-sec-to-50ft criterion, represents mainly a level of power-on stall margin. Generally speaking, the popup maneuver can be performed only if the V/V_{SPA} ratio is about 1.2. Hence, the existing 1.1 V_{SPA} minimum-speed criterion is not likely to be critical and its necessity is open to question.

Also, the 5-sec-to-50ft criterion is an open-loop maneuver in which the short-term response factor is only weakly represented. A modification of the maneuver that includes maintenance of glideslope (such as the “7-sec-to-50ft-and-back-to-50ft” version used at one time) would strengthen the short-term response attribute implicit in the maneuver.

- **The “minimum potential flightpath lag” is a useful short-term response metric.**

The *minimum potential flightpath lag* is the rise-time-to 63% for a well-coordinated step input of pitch attitude and thrust. It is a short-term response metric that embodies the airframe and control system features in the context of a well-refined pilot technique. Also it is directly computable for the open-loop aircraft system. Competing but more simplistic metrics include, Z_w, T_{θ_2}, and $V \cdot n_{z\alpha}$.

- **Thrust-lag is mainly an “inner-loop” control problem.**

The effect of thrust lag on the total short-term response (minimum potential flightpath lag) is small compared to the effects of basic heave damping ($T_{\theta 2}$) and the effective pitch attitude response. Therefore one can deduce that thrust lag is an *inner-loop* control problem under some conditions. This would be true for aircraft having quick airframe and pitch response but receiving engine-response complaints.

One can relate thrust lag to the pilot's ability to adjust thrust, given that engine sound is the only status cue. Using the Hess analytical approach, the boundary for pilot acceptance was estimated. The current 1.2 sec rise-time-to-90% criterion coincides with the knee in the Hess criterion estimate, and it agrees numerically with the bandwidth criterion for inner-loop pitch response.

- **“Last significant glideslope correction” is an extension of the popup criterion.**

The main requirements for effective flightpath control rest upon answering simultaneously how *quick*, how *large*, and how *precise* can the pilot perform a terminal flightpath maneuver. The *last significant glideslope correction* is a math model formulation aimed at obtaining such an answer for the carrier landing task.

Airframe and control features are lumped into a low-order math model and a feedback loop closed around them. It is used here to explore the effects of several design parameters. This analysis method is a sophistication of the popup maneuver that potentially incorporates multiple aspects of the pilot-vehicle-task system.

This method demonstrates the influences of several control factors, particularly short-term response. Tentative conclusions were made based on LSO task performance assumptions, but only to demonstrate the method. Firmer results depend upon analysis of actual carrier landing data involving large, close-in terminal maneuvers along with pilot and LSO assessments of acceptability.

- **Carrier landing task-performance can be defined using existing facilities.**

The main objective of quantifying task performance in the carrier approach is to assist in setting design and test criteria. Given the heavy reliance on computer-aided design and simulation in the design process, task performance standards can be factored-in at the earliest stages.

It is desirable to determine the quantitative nature of each task-performance feature through direct measurement, including:

(i) how *aggressively* the pilot needs and desires to make flightpath corrections,
(ii) how *large* they might be (presumably as a function of range),
(iii) what degree of closed-loop *damping* or *settling i*s needed, and
(iv) how *precise* in order to meet terminal conditions with high likelihood of success.

Each of these can be quantified, measured, and reduced to basic design factors.

Existing analysis techniques and flight-test measurement facilities are fully capable of collecting and organizing these specific task-performance data. The main requirements are to obtain precise position data and to obtain it in the context of an actual carrier environ ment. Both presently are feasible.

While an analysis of some laser-tracker data was performed, it was not possible to arrive at any definitive assessment of how the carrier landing task is carried out in useful engineering terms. An initial phase-plane analysis was done to examine pilot aggressiveness and maneuver amplitude for the FCLP data available, and this showed a general degree of consistency from run to run and from one aircraft to another. But without accompanying pilot commentary and a full knowledge of the circumstances of each approach, there is some danger in over-analyzing such data. Also, they did not fully represent an actual carrier environment and therefore lack credibility.

5.2 Need for Further Research

Based on this study, primarily an analytical effort, there are several gaps in existing design requirements as indicated above. Also there is reasonable doubt of the effectiveness of some requirements now in use. Future research should address several items, both experimentally and by non-intrusive in-flight measurements. This work should focus on the carrier landing task but also should include, where possible, other tasks and mission elements for which manual control is crucial. The following items describe briefly the logical steps in any future program to achieve these goals.

- **Analyze quantitatively examples of carrier-landing task performance.**

First, there is a need to make a comprehensive survey parameters which describe the carrier landing task. One main objective should be to quantify for several aircraft types the maximum desired level of aggressiveness in control of flightpath as a function of range from the ship. This must be done with highly skilled and experienced carrier pilots. It should include both glideslope and lineup tasks. Aircraft instrumented for laser-tracker position measurement should be used in all cases. The *last significant glideslope correction* is a model about which task performance data can be gathered and organized.

- **Develop a simulator experimental test program.**

The second step should be to design a flight-simulator experiment that systematically explores the design parameters identified in this study. It is necessary to confirm their importance and structure a comprehensive framework for outer-loop-control design requirements. The design of an experiment needs to be based partly on the analyses presented in this report and on some subsequent, more detailed analyses.

- **Conduct a simulator experiment.**

Following the experimental design, a simulator experiment should be carried out to gather the needed data. This should be done using facilities and pilot subjects that are suited to examining the Navy carrier landing mission. Objective data should include all task performance measurements gathered for in-flight carrier landing examples. Subjective data should contain pilot commentary and Cooper-Harper ratings.

- **Verify simulator results with flight tests.**

The simulator results must be verified by selected in-flight testing. This is possible using non-intrusive test pilot evaluations made during routine carrier-suitability flight testing. This needs to be done either during the simulator program or shortly following it and with some of the same pilots who participate in the simulations.

- **Propose outer-loop-control requirements.**

The final step is to prepare a comprehensive report documenting all analytical, experimental, and flight verification work along with a proposal for outer-loop control requirements. This needs to be done with the cooperation and participation of representatives from several disciplines, including *stability and control, aircraft performance,* and *carrier suitability testing.* This team-effort report thus would serve as the basis for any needed revision of existing design requirements.

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GLOSSARY

This glossary defines several technical terms as they are used in this report. These terms describe aspects of the Navy carrier aircraft environment, airplane flight dynamics, and manual control theory.

airspeed	A general term that can include true airspeed, calibrated airspeed, indicated airspeed, or equivalent airspeed. For Navy aircraft it can refer to angle of attack as it is viewed as a speed indication. These distinctions are neglected here although angle of attack is generally specified when it is involved explicitly.
angle of attack	The angle between the fuselage reference line and the relative wind. It is the primary speed reference for Navy aircraft in low-speed or approach conditions.
AOA	An acronym for angle of attack.
backsidedness	The general quality describing the thrust-required operating point with respect to airspeed. It can be defined as the partial derivative $\partial \gamma / \partial V$ taken from a plot of trimmed flightpath angle versus airspeed, or alternatively, as the value of the numerator coefficient $1/T_{h1}$. It has several interpretations, including "speed stability" for a single-loop closure on flightpath with pitch-attitude or elevator control. Backsidedness specifically occurs when the proportion of induced drag exceeds the profile drag ($C_{D_i} > C_{D_o}$).
backside technique	A "compensatory" control technique in which thrust is used to control flightpath and pitch attitude is used to control speed (or angle of attack). It is commonly viewed as the appropriate technique for Navy aircraft, but there are fundamental and serious limitations on the closed-loop response if applied rigorously. The backside technique can also be applied to a trimmed condition on the frontside of the thrust-required curve. (See *frontside technique, compensatory.*)

bolter	Touching down on the deck but not engaging the tailhook with the arresting gear. In anticipation of a bolter the pilot always applies military thrust at touchdown to guarantee becoming airborne after passing over the deck. Thus the consequences of a bolter are similar to a waveoff.
BRC	The "base recovery course" or direction of the ship. It differs from the final-approach-leg heading by the deck cant angle and a small function of the wind.
break	The decelerating-turn maneuver used to transition from the initial upwind leg to the downwind leg of the approach.
chevrons	The AOA indexer lights above and below the doughnut that indicate a fast or slow condition. The upper chevron indicates a slow condition and points toward a nose-down correction. The lower chevron is the reverse. (See *doughnut, indexer.*)
closure speed	The relative speed between the aircraft and ship as set by the speed of the ship and the wind speed.
compensatory	A general manual control-loop structure in which the pilot uses one control to regulate one state and a second control for a second state. The amount of control used is in strict proportion to the perceived error weighted with error rate (lead) and error standoff (time-integral). “Compensatory” loop structure is simpler than “pursuit” but is likely to yield inferior performance. The “backside” technique is an example of a compensatory structure: If a glideslope error is detected, the pilot applies thrust in proportion to the error but leaves pitch attitude unchanged; when a speed error is detected, the pitch attitude is adjusted and thrust is maintained.
control power	The maximum sustainable size of change for a state variable or control. Here the term is used mainly in conjunction with flightpath angle or vertical velocity. It normally is used to describe maximum available angular rates or accelerations. It can be applied to translational accelerations.

denominator	Refers to the component of a transfer function that contains the modal response factors. A first-order denominator root corresponds to an exponential mode and a second-order root a damped sinusoidal mode. For traditional longitudinal equations of motion the denominator consists of the phugoid (ζ_p, ω_p) and short-period (ζ_{sp}, ω_{sp}) modes. For attitude-constrained equations of motion there are two first-order modes, heave damping ($1/T_{\theta 2}$) and speed damping ($1/T_{\theta 1}$).
doughnut	The round light on the AOA indexer that indicates an on-speed condition when illuminated. (See *chevrons, indexer.*)
flightpath	A general term describing the translational motion in either the vertical or horizontal plane. In the vertical plane it can include flightpath angle, glideslope error or error rate, altitude, or vertical velocity; in the horizontal plane it can include lateral displacement, lateral velocity, or lateral flightpath angle.
flightpath angle	The instantaneous direction of flight as given by the difference between pitch attitude and angle of attack. Symbols are γ (absolute) or $\Delta\gamma$ (incremental).
FLOLS	The acronym for the Fresnel Lens Optical Landing System, a device that gives a continuous visual indication of glideslope error. It is physically situated on the portside about midway along the deck, but the focus of the glideslope is 150 ft forward of the physical system.
frontside technique	A “compensatory” control technique in which the pilot adjusts pitch attitude control flightpath and thrust to control speed (or angle of attack). It is commonly viewed as being appropriate only for "frontside" operating conditions but this is not entirely correct, it can be used by the pilot even though the aircraft is trimmed on the “backside” of the thrust-required curve. The frontside technique has fundamental benefits with respect to bandwidth potential over that of the backside technique. (See *backside technique, compensatory.*)

FRL	Aircraft fuselage reference line, the primary x-axis reference designated by the manufacturer. In this report angle of attack is taken with respect to the FRL.
glideslope	The nominal vertical-plane path leading to the touchdown point. The origin is at the focus of the FLOLS (about 150 ft beyond the physical assembly) and the nominal angle is set at 3.5° to 4° . The beam centerline also can be adjusted vertically by rolling the plane of the beam off-axis from the centerline. This is done to adjust the "hook-to-eye" distance that is peculiar to each aircraft type.
glideslope error	The angular error between the actual aircraft position and the nominal glideslope. The error is displayed to the pilot via the FLOLS.
heave damping	The proportion of aerodynamic to inertial forces in the vertical axis. It is normally represented by the dimensional stability derivative Z_w but is also often equated to the response coefficient $1/T_{\theta 2}$. The main aerodynamic component is the non-dimensional derivative $C_{L\alpha}$. (Speed damping its counterpart in the longitudinal axis.)
hook-to-eye distance	The nominal vertical distance between the paths of the pilot's eye and the tailhook when the aircraft is at its prescribed approach speed. This dimension is factored into the FLOLS setup for each aircraft type and, sometimes, for different flap positions.
HUD	Acronym for Head-Up Display.
indexer	The glareshield-mounted AOA light display containing doughnut and chevron symbols.
LSO	The Landing Signal Officer assigned to assist the pilot during the final approach from a vantage point adjacent to the landing area. The LSO maintains voice contact with the pilot and uses a prescribed set of oral commands. In addition, the LSO can signal a waveoff with lights mounted on the FLOLS assembly.

meatball	The Fresnel lens presentation of glideslope error. It is a yellow light (red for the lowest cell) which moves relative to a horizontal row of datum lights. The sense of the meatball is “fly-from.”
NATOPS	Manuals issued in conjunction with the Naval Air Training and Operating Procedures Standardization Program. Each aircraft model has a NATOPS flight manual, and there is an LSO NATOPS manual.
numerator	The transfer function component that contains the “gain” and the “zeros,” factors that are peculiar to the particular transfer function state and control combination and modify the degree of excitation of each response mode. For example, the N^{α}_{θ} numerator applies to the response of angle of attack to a pitch attitude change. The roots of this numerator are very nearly coincident with the phugoid mode. Therefore, any modal response near the phugoid tends to be diminished. Also, should angle of attack be constrained with pitch inputs, the resulting dominant response will be a phugoid motion. (See *denominator*).
n_{z_α}	A partial derivative, $\partial n_z/\partial \alpha$, which describes the instantaneous sensitivity of normal acceleration to angle of attack or, alternatively, to pitch attitude. It is a fundamental design parameter that enters several factors, including $1/T_{\theta 1}$, $1/T_{\theta 2}$, and the magnitude of pitchup in the popup maneuver. It is computed easily by taking the ratio of trimmed $C_{L\alpha}/C_L$.
pitch attitude	The angle between the FRL and the horizontal plane.
pitch-attitude-constrained	The assumption that pitch attitude is effectively an independent or control variable, but not that pitch attitude is necessarily held constant. It is a condition used to gain simplification of the equations of motion when flightpath and speed are the main state variables of interest.

pursuit	A more sophisticated level of pilot control structure than “compensatory” and recognizes that the pilot can coordinate (crossfeed) two controls to enhance response of one state while minimizing the disturbance of others. It reflects the pilot's ability to apply his knowledge of the vehicle response to his control technique. Normally there is a combined benefit of enhanced response and lower workload over the more basic “compensatory” level of control. An example of a pursuit technique is the pilot's blending of pitchup and increased thrust when making and upward flightpath correction. Another example would be the converse for an increased speed correction, namely, pitching up while decreasing thrust. A pilot typically develops a pursuit control structure as a natural result of experience.
ramp	The aft edge of the deck landing area on an aircraft carrier. A “ramp-strike” accident occurs when an aircraft undershoots the landing area and impacts the aft portion of the deck. During a normal approach, the aircraft is “at the ramp” when about 600 ft aft of the touchdown point.
speed damping	The proportion of aerodynamic force to inertial force along the longitudinal (x-) axis. It is represented normally by the dimensional stability derivative X_u but is more correctly equated to the response coefficient $1/T_{\theta 1}$ (in contrast to heave damping).
T_{h1}	A transfer function factor found in the γ/θ, d/θ, $\gamma/\delta e$, or $d/\delta e$ numerators that represents the degree of “backsidedness” or “frontsidedness.” Normally it is expressed as the inverse, $1/T_{h1}$. For $1/T_{h1} > 0$ the aircraft is on the frontside of the thrust-required curve (the slope of $\partial \gamma/\partial V$ is negative).
$T_{\theta 1}$	A transfer function factor that represents a surge-motion (speed-damping) exponential-response mode for pitch-attitude-constrained conditions. If an axial force is applied the airspeed increases exponentially with a time constant of $T_{\theta 1}$.

$T_{\theta 2}$	A transfer function factor that represents a heave-motion (heave-damping) exponential-response mode for pitch-attitude-constrained conditions. The value of $T_{\theta 2}$ is approximately $-1/Z_w$. $1/T_{\theta 2}$ is essentially the limiting bandwidth for flightpath response with the most favorable piloting technique.
wire	A general term that refers to the cross-deck pendant portion of the ship's arresting cable system. Normally there are four wires with the #1 wire closest to the ramp.

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