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OUTER-LOOP CONTROL FACTORS FOR CARRIER AIRCRAFT

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19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

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.

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.

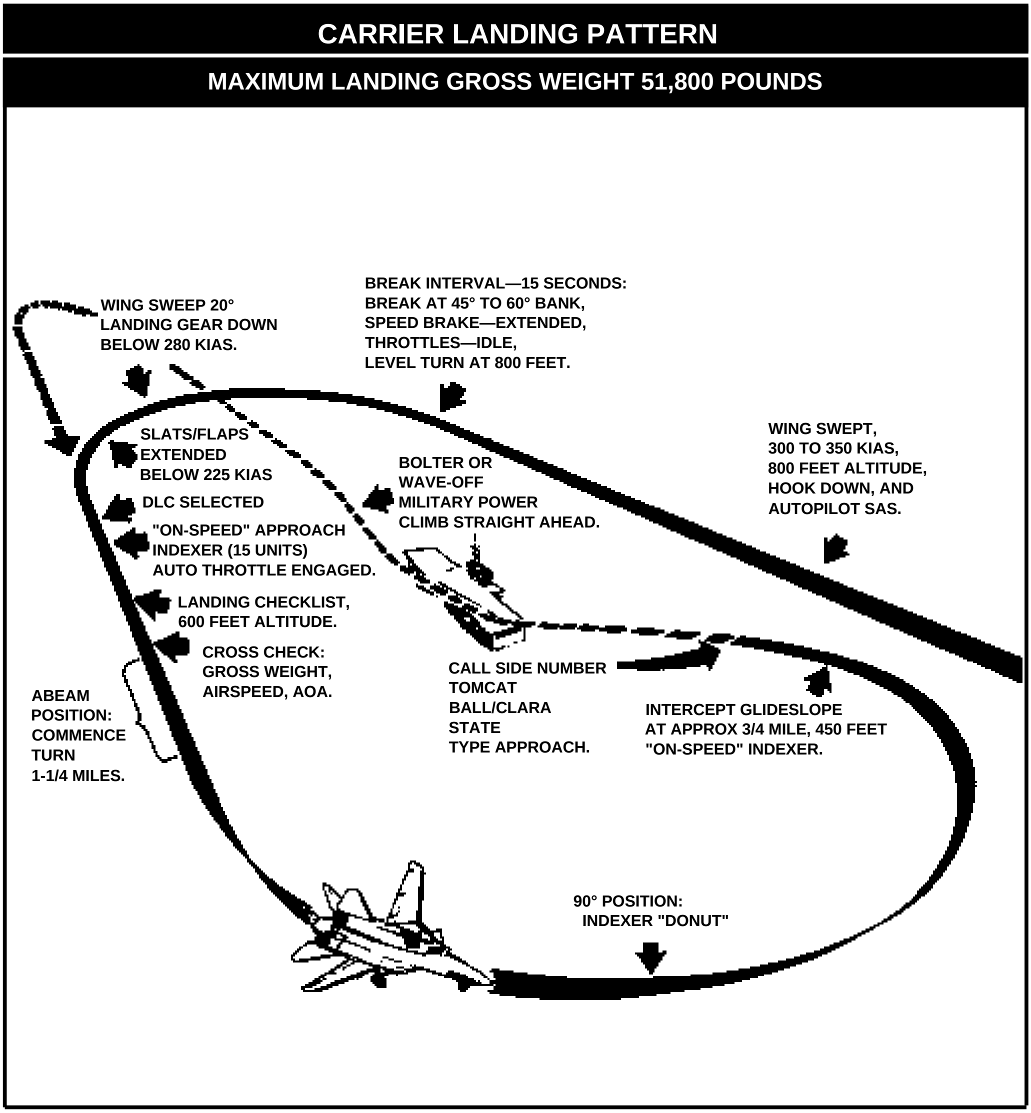

Figure 2-1. Carrier Landing Pattern as Described in NATOPS.

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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]

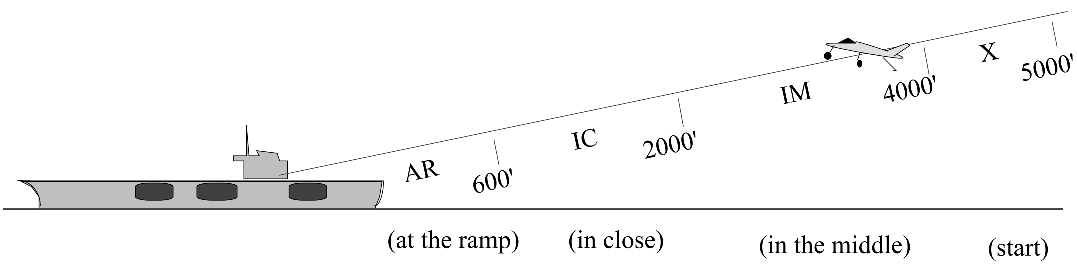

Figure 2-2. LSO Range Descriptors.

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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.

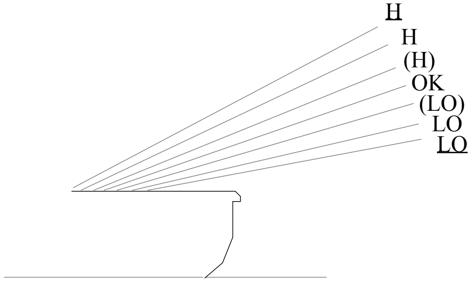


Figure 2-3. LSO Glideslope Descriptors.

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]

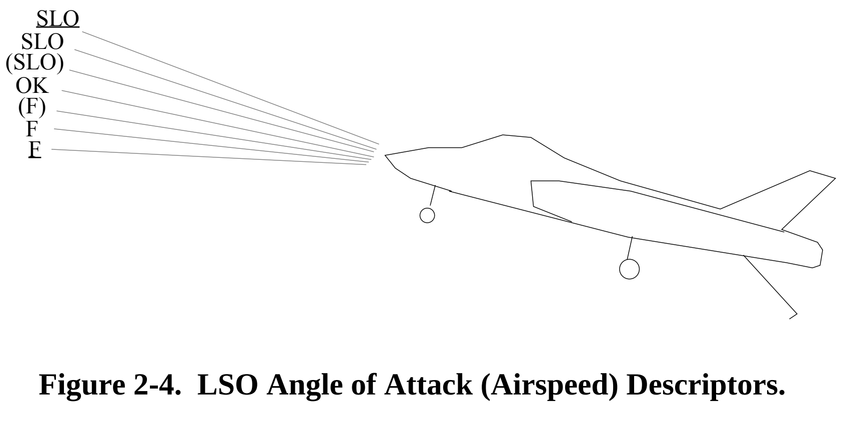


Figure 2-4. LSO Angle of Attack (Airspeed) Descriptors.

[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.

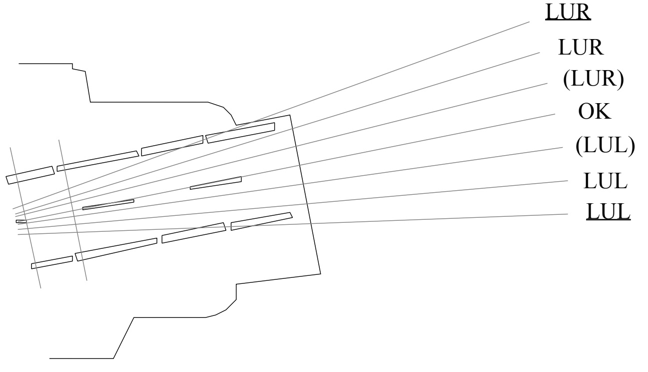


Figure 2-5. LSO Lineup Descriptors.

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]

[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	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	LO	-1.6°	well below FLOLS beam (~5 balls low)

Angle of Attack (Speed):

verbal description	*symbol*	*value*	*meaning*
very slow	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	F	-3 units	nose-up chevron (red)

Lineup Position:

verbal description	*symbol*	*value*	*meaning*
lined up very far rt	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	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	TMRD	-.4 °/sec	

Drift Rate:

verbal description	*symbol*	*value*	*meaning*
very fast right drift	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	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.

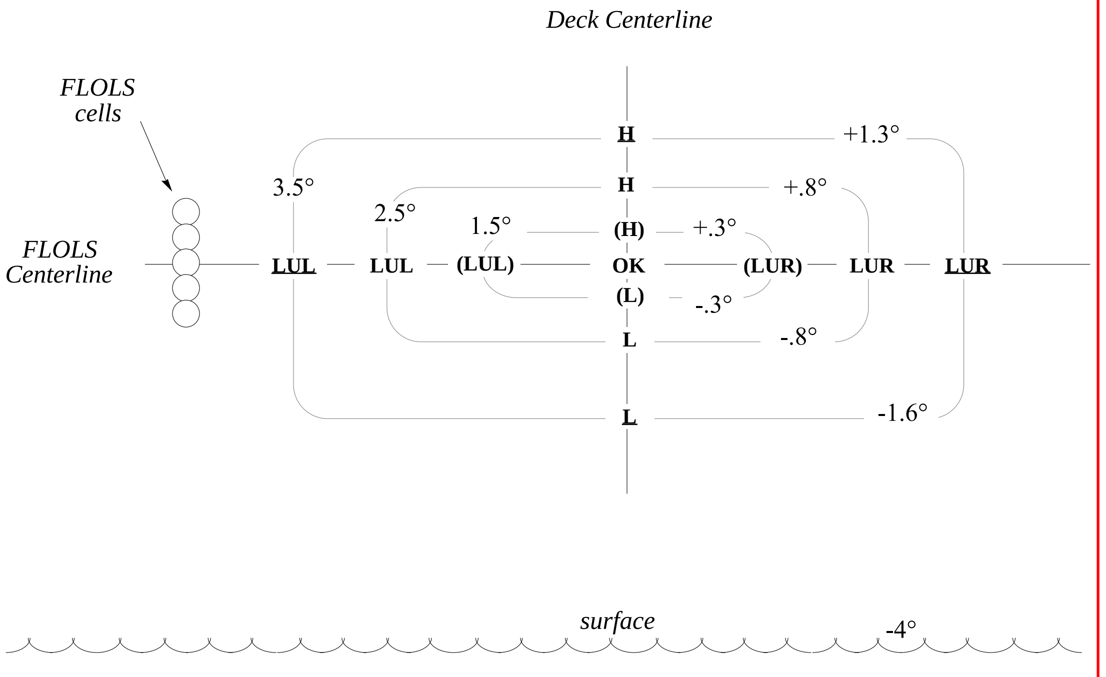


Figure 2-6. Scale Drawing of Approach Flightpath Parameters.

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.)

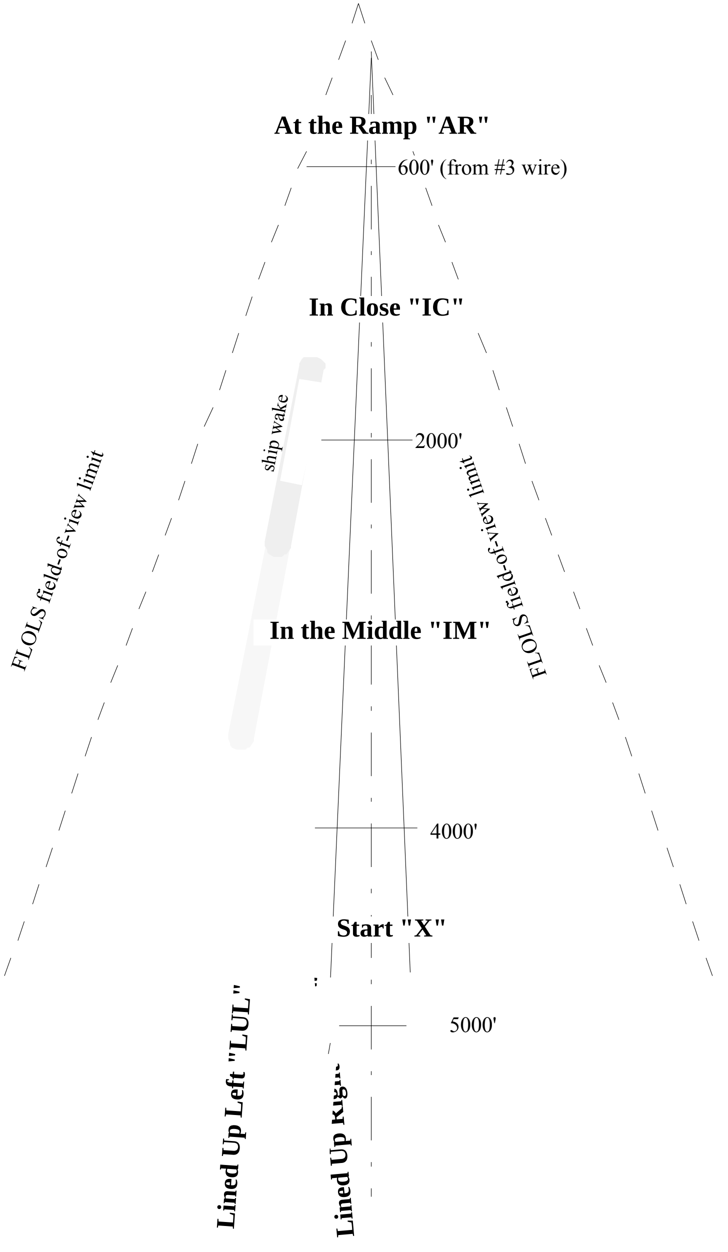


Figure 2-7. Planview of Final Approach Leg.

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.

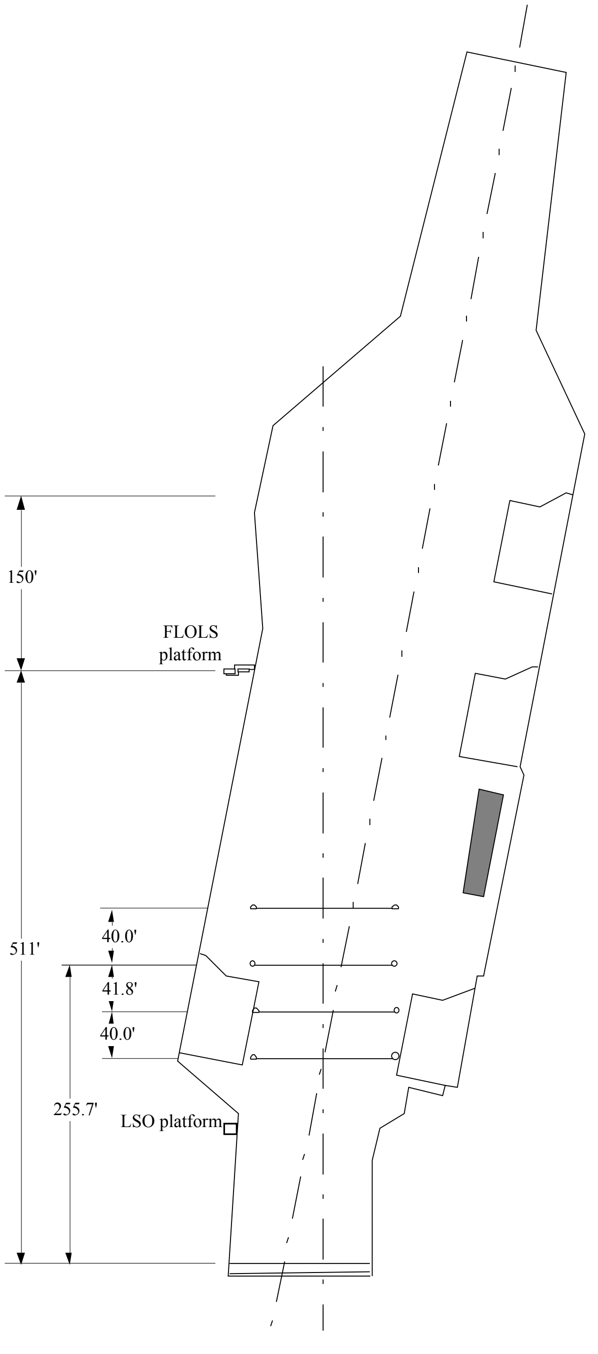


Figure 2-8. Planview of Carrier Deck.

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 not 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., OSX, NESA HFX, HFX, 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 reductions 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.

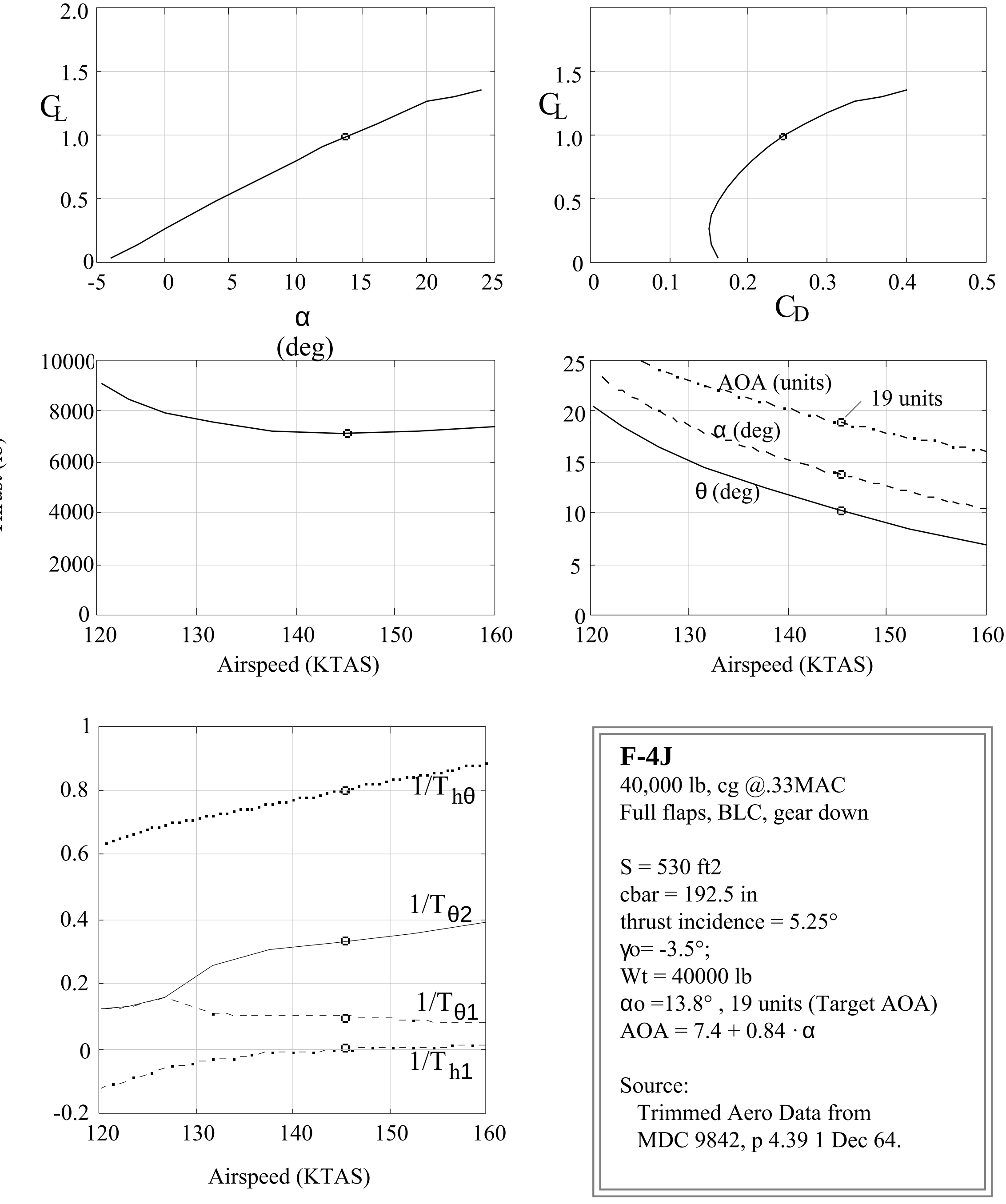
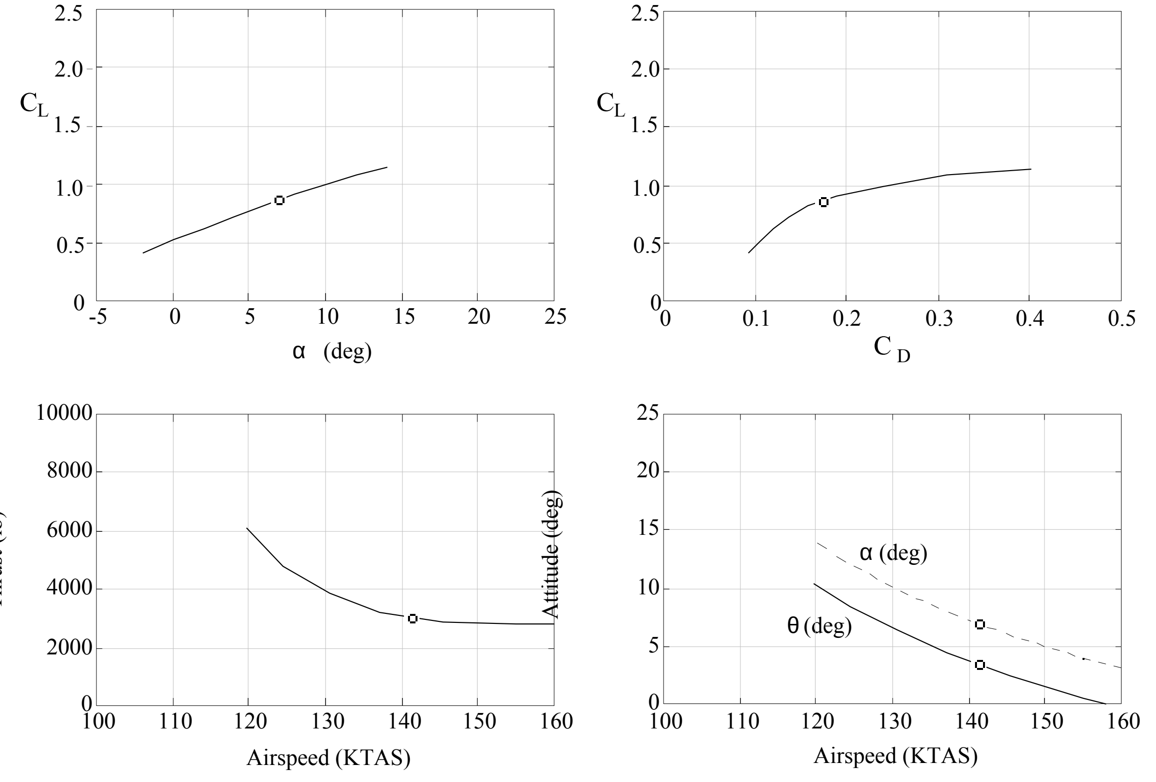
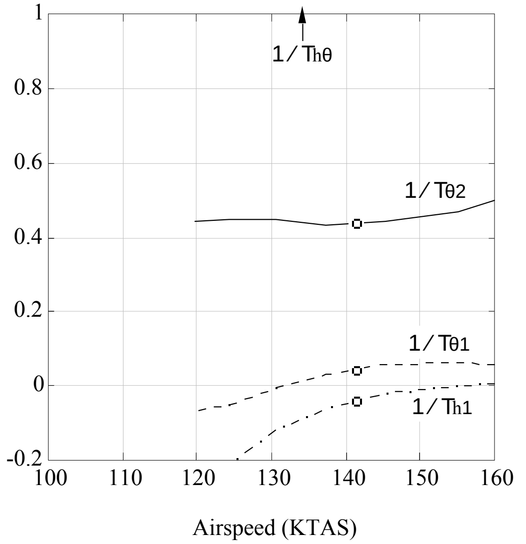


Figure 2-9. Summary of F-4J Aero, Trim, and Response Parameters.





F-8C

22,500 lb, cg @.30MAC

Full flaps, Gear down

$S = 375\ ft^2$

cbar = 11.78 ft

thrust incidence = .85°

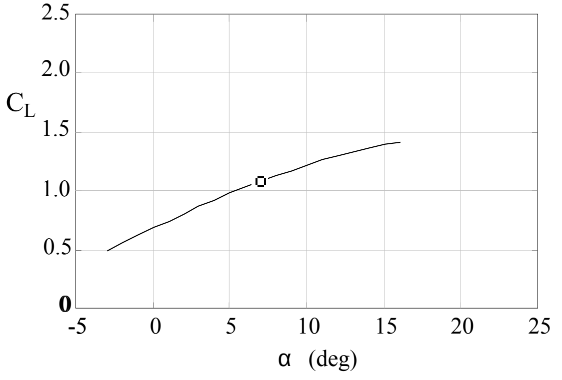
$\gamma_0 = -3.5°$;

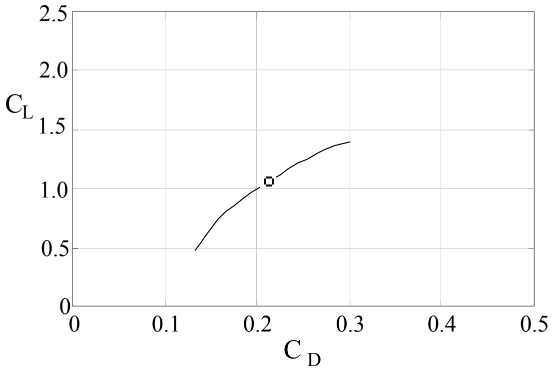
$\alpha_0 = 7°$

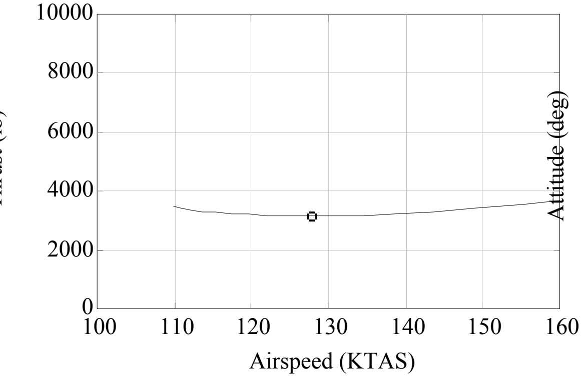
Source:

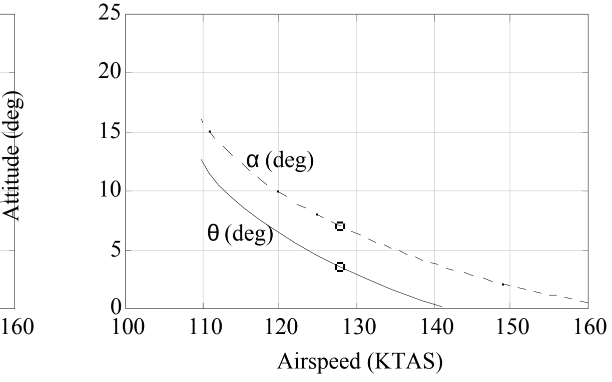
LTV Report EOR-13202 of 25 Oct 1960.

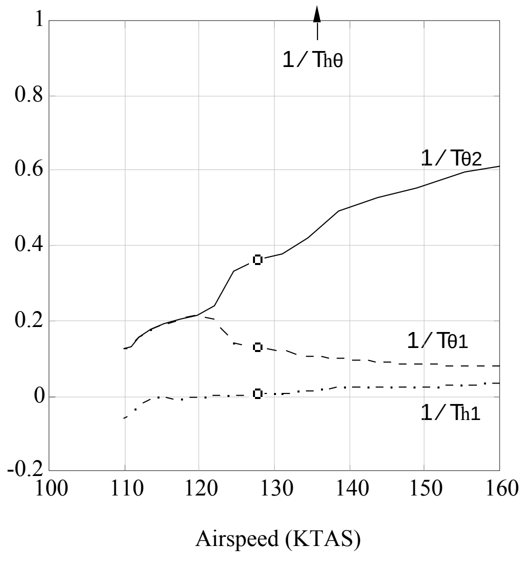
Figure 2-10. Summary of F-8C (no BLC) Aero, Trim, and Response Parameters.











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.

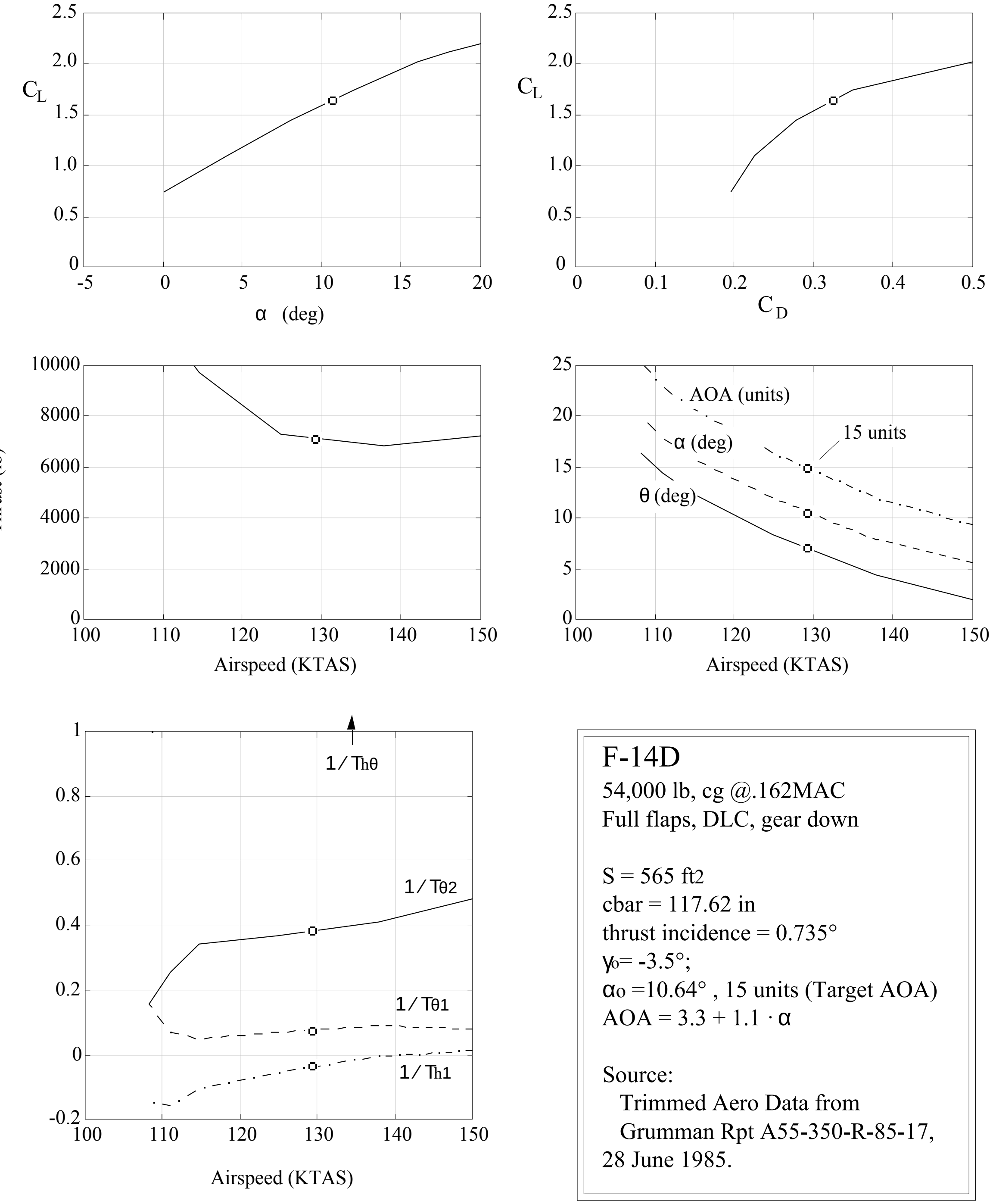


Figure 2-12. Summary of F-14D Aero, Trim, and Response Parameters.

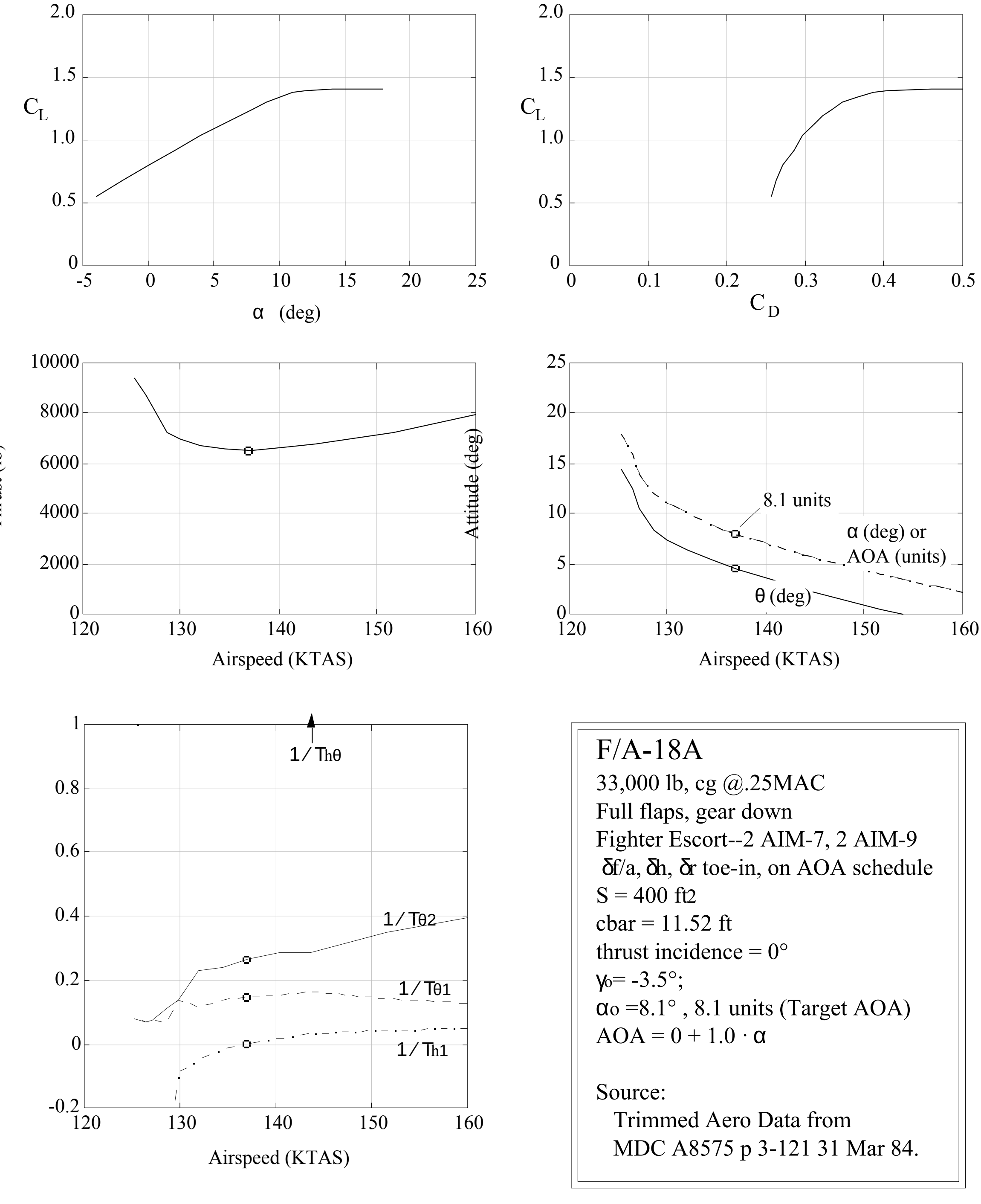


Figure 2-13. Summary of F/A-18A Aero, Trim, and Response Parameters.

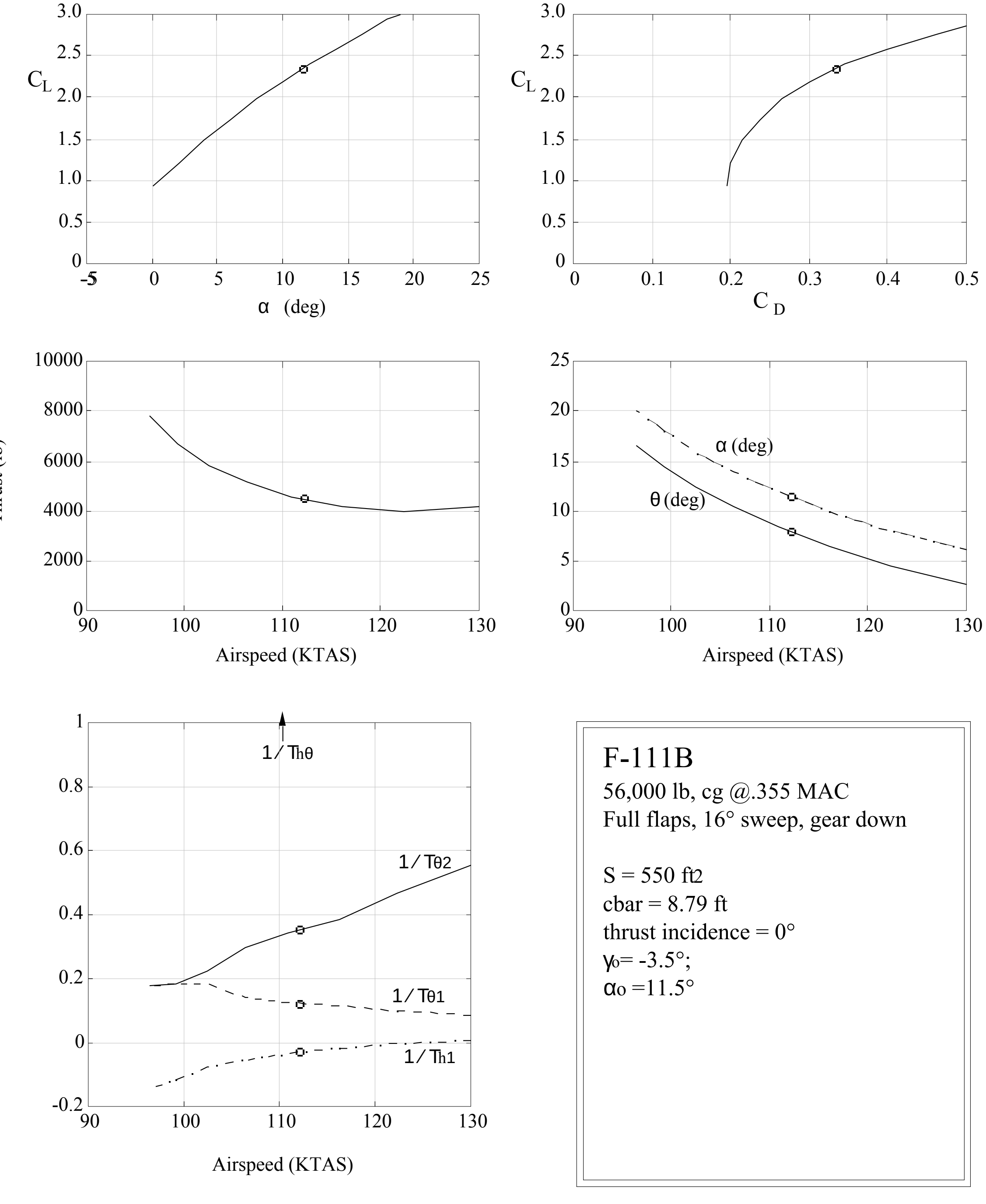


Figure 2-14. Summary of F-111B Aero, Trim, and Response Parameters.

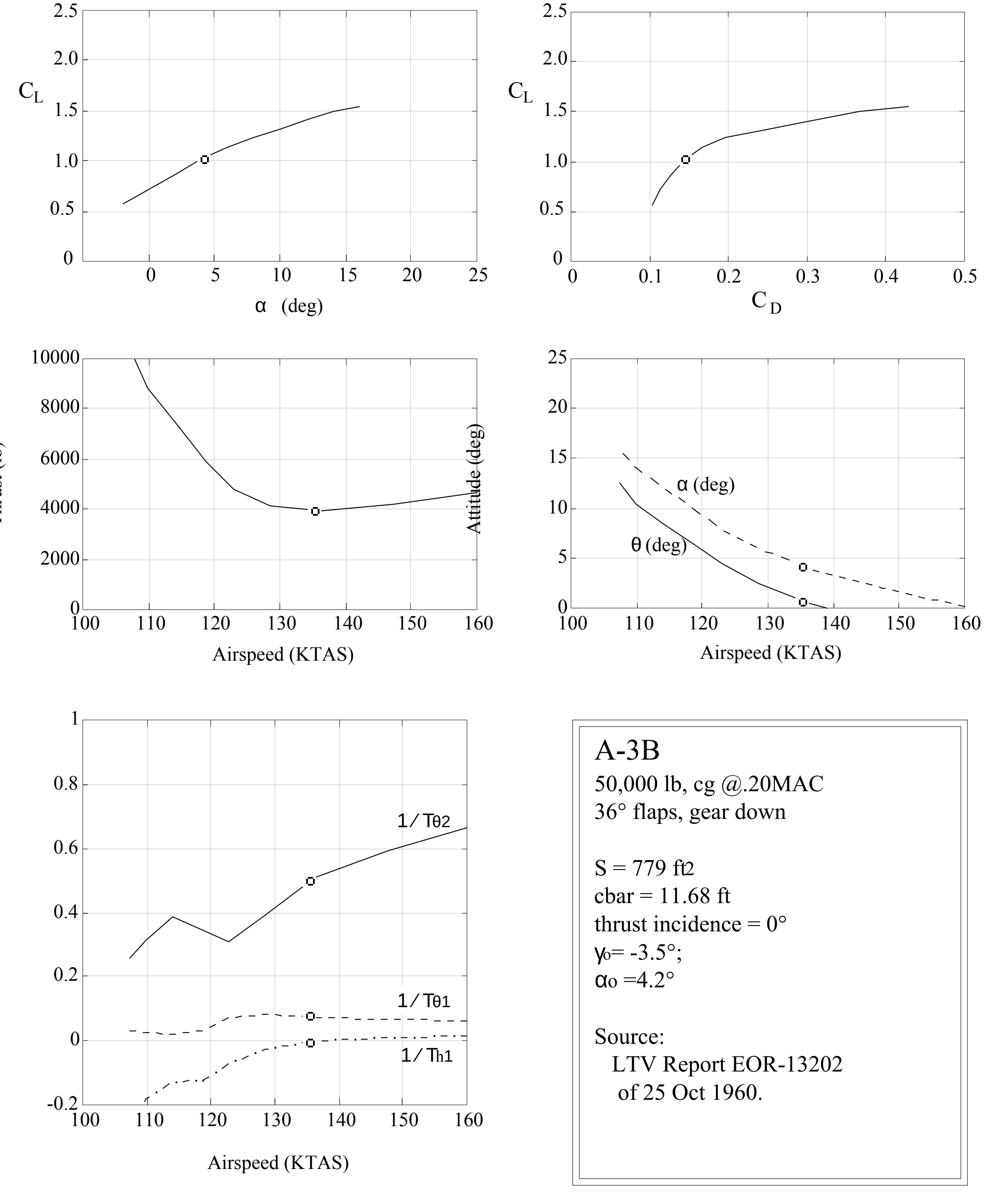


Figure 2-15. Summary of A-3B Aero, Trim, and Response Parameters.

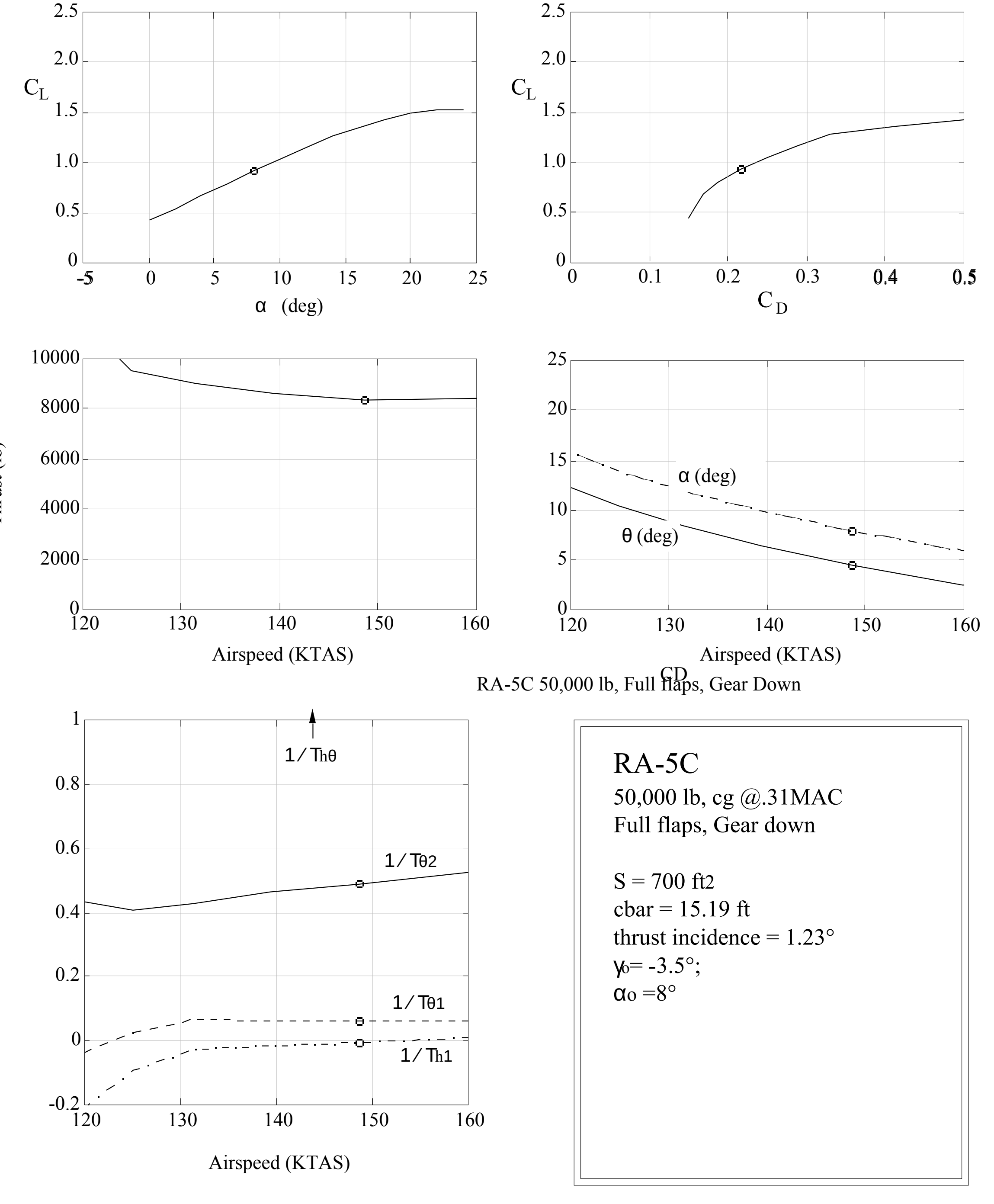


Figure 2-16. Summary of RA-5C Aero, Trim, and Response Parameters.

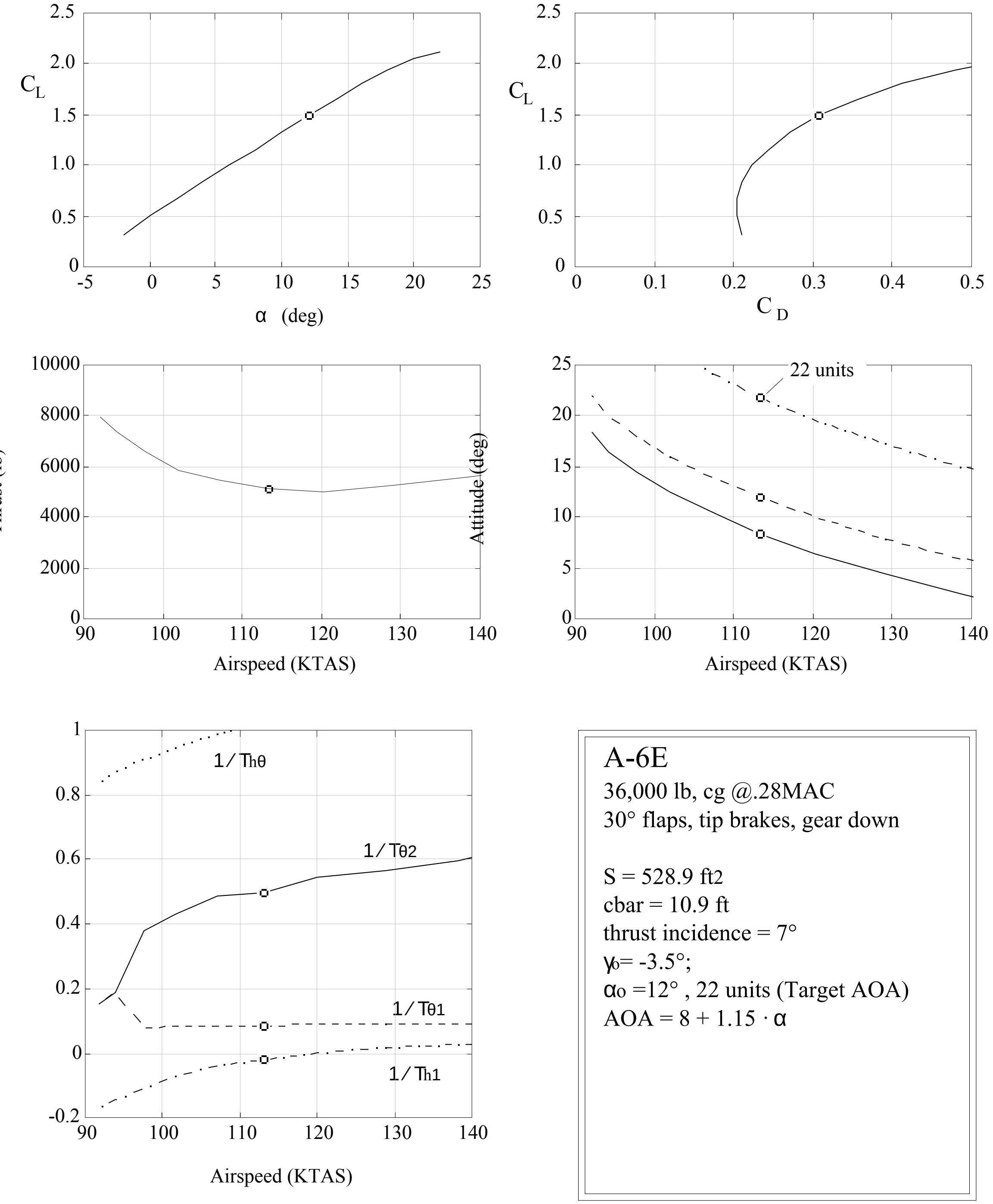


Figure 2-17. Summary of A-6E Aero, Trim, and Response Parameters.

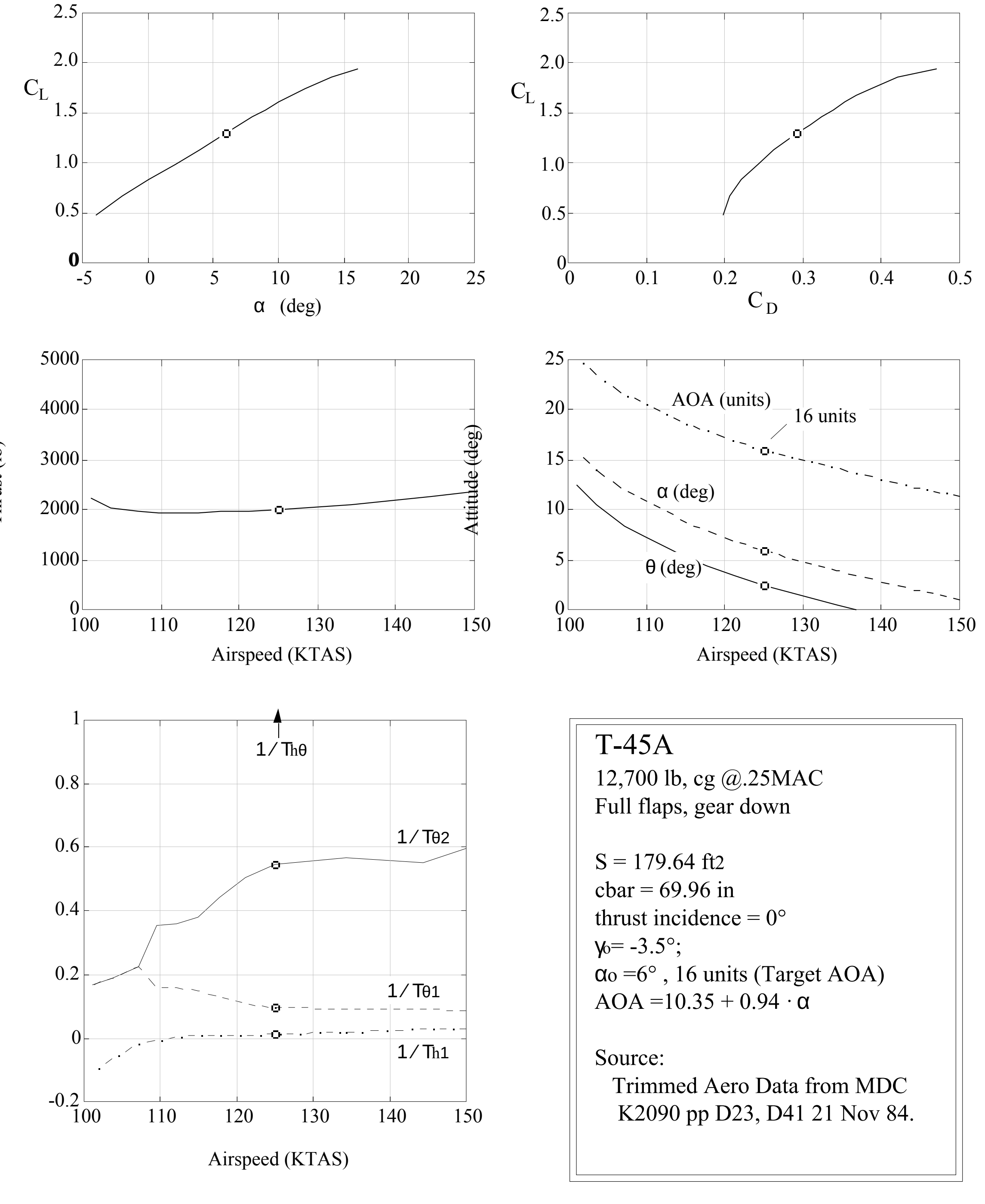


Figure 2-18. Summary of T-45A Aero, Trim, and Response Parameters.

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

*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.

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

[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.

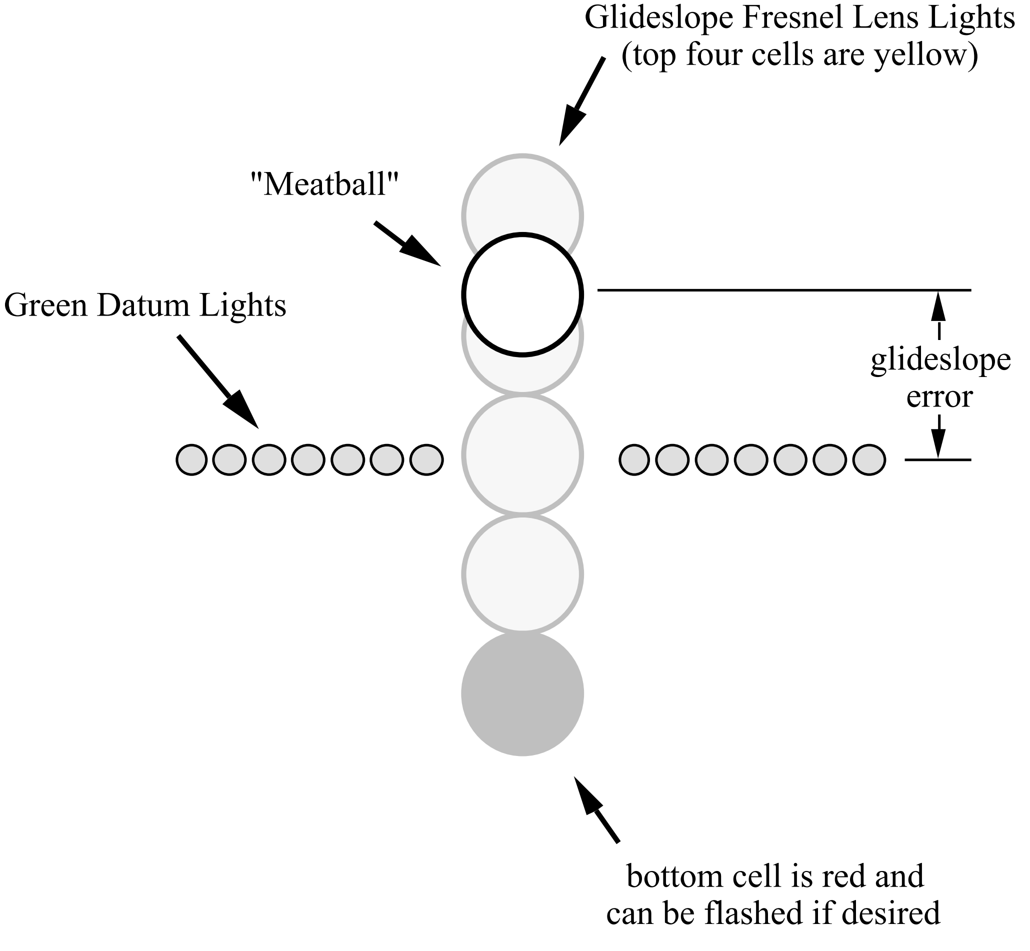


Figure 3-1. FLOLS Glideslope Display Geometry.

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.

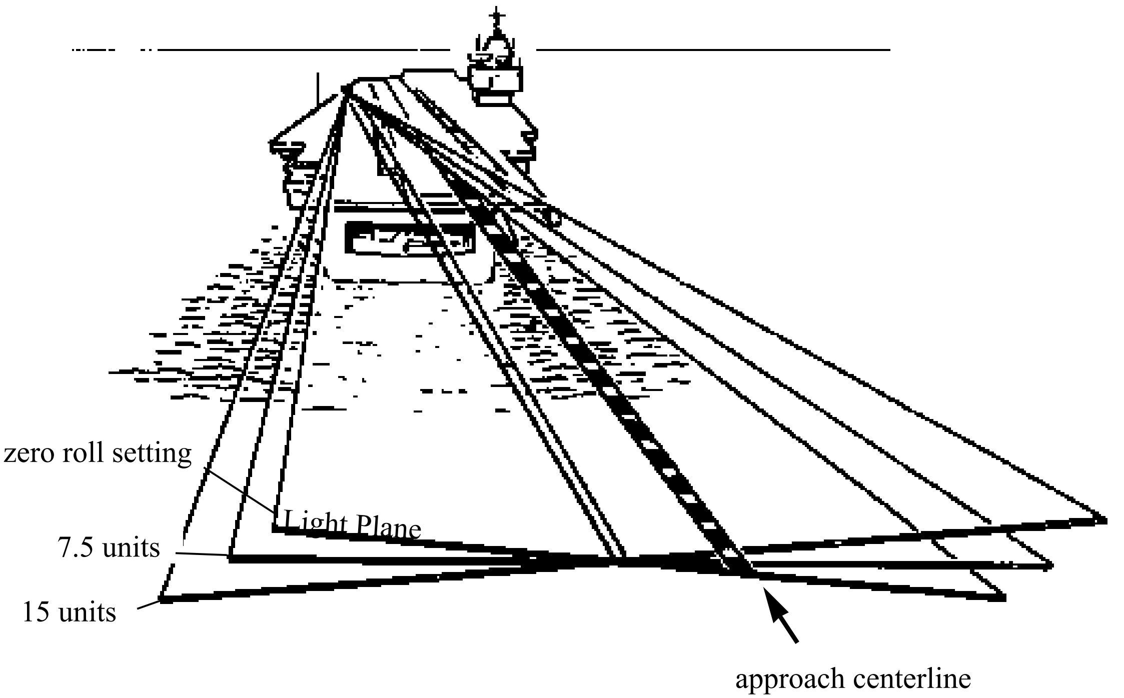


Figure 3-2. Effect of FLOLS Roll Angle on Light Plane.

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

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.

$\lambda \quad \arctan(y/h)$
where y is lateral offset
and h is altitude above deck.

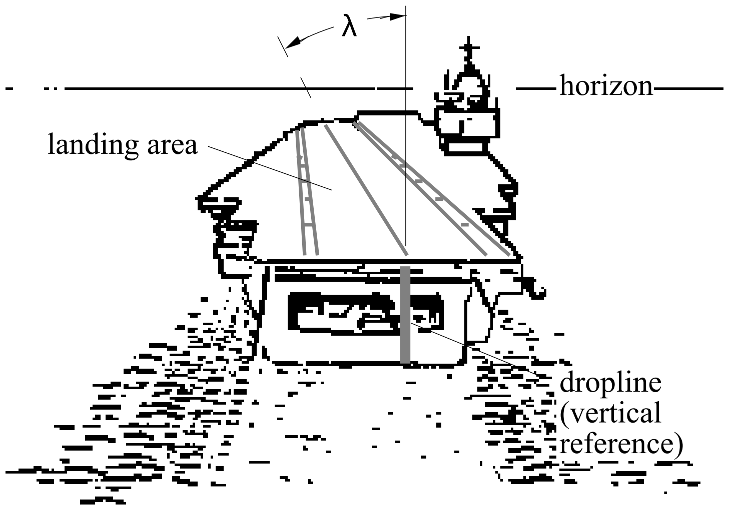


Figure 3-7. Lineup Geometry.

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.

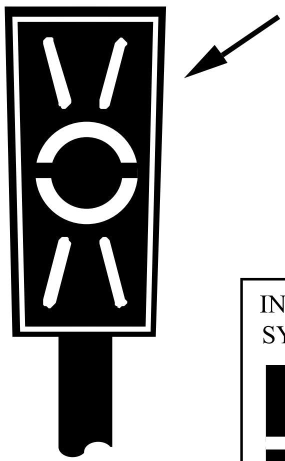
There is a great practical advantage to partitioning inner- and outer-loop features. One benefit is the analyst's understanding of the physical system. Another is that calculations are simple and checkable with reasonable effort. Finally, it is usually cheaper and faster to begin systems analysis with 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.

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

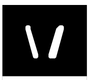
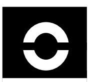
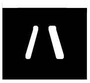
INDEXER SYMBOL	ANGLE OF ATTACK	APPROACH LIGHT COLOR (Visible to LSO)
	High α (Slow)	Green
	Slightly High α (Slightly Slow)	Amber
	Optimum α (On Speed)	Amber
	Slightly Low α (Slightly Fast	Amber
	Low α (Fast)	Red

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

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.

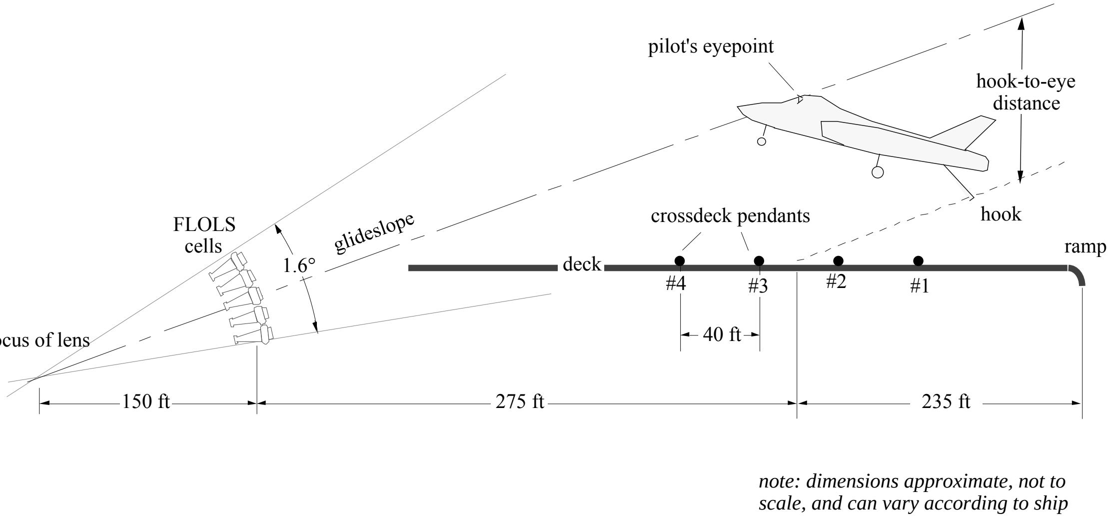


Figure 3-3. Sideview of FLOLS Geometry.

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