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THE POTENTIAL OF INTEGRATING GROUND TEST DATA INTO THE FLIGHT TEST INVESTIGATIONS FOR THE EVALUATION OF AIRCRAFT PERFORMANCE AND FLYING QUALITIES

A Thesis

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Steven C. Herzig

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ABSTRACT

A technical approach to efficiently integrating ground test data into the flight test investigations for the evaluation of aircraft performance and flying qualities is presented. This method relies on the coordinated efforts of an integrated test team representing the various ground and flight test organizations. Also, this approach involves taking maximum advantage of mathematical models to simulate and verify the system's operating characteristics. Although most of the modeling methods discussed are currently in use at Air Force flight test installations, the need to optimize their use by integrating the ground test predictions and techniques in an iterative manner is discussed. The evaluation of this process shows that the integrated test team approach to testing for aircraft performance and flying qualities is feasible, and offers distinct advantages over the segmented approach currently employed by the Air Force.

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NOMENCLATURE

AEDC	Arnold Engineering Development Center, Arnold AFB, Tennessee
AFB	Air Force Base
AFFTC	Air Force Flight Test Center, Edwards AFB, California
AFR	Air Force Regulation
AOA	Angle of Attack
a_x	Acceleration along the longitudinal axis
b	Aircraft wing span
c	Aircraft mean aerodynamic chord
CFD	Computational Fluid Dynamics
C_D	Drag coefficient
C_{D_α}	Change in drag coefficient with angle of attack
$C_{D_{\dot{\alpha}}}$	Change in drag coefficient with angle of attack rate
$C_{D\delta_e}$	Change in drag coefficient with elevator deflection
C_{D_o}	Drag coefficient bias when $\alpha = \delta_e = 0$
C_{D_q}	Change in drag coefficient with pitch rate
C_{D_u}	Speed-damping derivative
CG	Aircraft Center of Gravity
C_L	Lift coefficient
C_{L_α}	Lift curve slope
$C_{L_{\dot{\alpha}}}$	Change in lift coefficient with angle of attack rate
$C_{L\delta_e}$	Change in lift coefficient with elevator deflection
$C_{L_{max}}$	Maximum attainable lift coefficient
C_{L_o}	Lift coefficient bias when $\alpha = \delta_e = 0$
C_{L_q}	Change in lift coefficient with pitch rate

C_{L_u}	Change in lift coefficient with velocity
C_l	Rolling moment coefficient
C_{l_β}	Dihedral effect
$C_{l_{\dot\beta}}$	Change in rolling moment coefficient with sideslip rate
$C_{l_{\delta e}}$	Roll (lateral) control power
$C_{l_{\delta r}}$	Roll due to rudder
C_{l_p}	Roll damping
C_{l_r}	Change in rolling moment coefficient with yaw rate
C_m	Pitching moment
C_{m_α}	Longitudinal static stability
$C_{m_{\dot\alpha}}$	Change in pitching moment coefficient with angle of attack rate
$C_{m_{\delta e}}$	Elevator power
C_{m_o}	Pitching moment coefficient bias where $\alpha = \delta_e = 0$
C_{m_q}	Pitch damping
C_{m_u}	Velocity stability
C_n	Yawing moment coefficient
C_{n_β}	Directional (Weathercock) stability
$C_{n_{\dot\beta}}$	Change in yawing moment coefficient with sideslip rate
$C_{n_{\delta a}}$	Adverse (or Proverse) yaw
$C_{n_{\delta r}}$	Rudder power
C_{n_p}	Change in yawing moment coefficient with roll rate
C_{n_r}	Yaw damping
C_y	Side force coefficient
$C_{y_{\dot\beta}}$	Side force damping
$C_{y_{\dot\beta}}$	Change in side force coefficient with sideslip rate

$C_{y_{\delta a}}$	Change in side force coefficient with aileron deflection
$C_{y_{\delta r}}$	Change in side force coefficient with rudder deflection
C_{y_p}	Change in side force coefficient with roll rate
C_{y_r}	Change in side force coefficient with yaw rate
D	Aircraft drag
deg	Degree
Diff	Difference
D_P	Propusive drag; sum of inlet, nozzle and ECS drags
DPS	Digital Performance Simulation
DT&E	Development Test and Evaluation
EPR	Engine Pressure Ratio; P_{t6}/P_{t2}
EU	Engineering Units
FCS	Flight Control System
F_E	Engine drag; $F_E = F_R + D_P$
F_{ex}	Excess thrust
F_G	Gross thrust
F_N	Net thrust
FPA	Flight Path Accelerometer
F_R	Ram drag
FRA	Frequency Response Analysis
F_S	Longitudinal stick force
ft	Feet
h	Acceleration due to gravity
H	Altitude
h_m	Maneuver point

h_n	Natural point
H_{pc}	Position error corrected altitude
HQDT	Handling Qualities During Tracking
IDLE	Idle thrust level
IDS	Integrated Data System
IFTD	In-flight Thrust Deck
INS	Inertial Navigation System
I_{xx}	Roll moment of inertia
I_{xz}	Product of inertia
I_{yy}	Pitch moment of inertia
I_{zz}	Yaw moment of inertia
KCAS	Knots Calibrated Airspeed
kts	Knots
L	Aircraft lift
M	Mach number
m	Aircraft mass
MAX	Maximum; maximum thrust level with afterburner
MIL	Military; maximum thrust level without afterburner
Mil Spec	Military Specification
MIN	Minimum
min	Minute
MIS	Management Information System
MMLE	Modified Maximum Likelihood Estimator
M_{pc}	Position error corrected Mach number
n	Load factor

NAM	Nautical Air Mile
N1	Low pressure compressor speed
N2	High pressure compressor speed
n_{max}	Maximum load factor
n_{min}	Minimum load factor
N_{zmax}	Maximum vertical load factor
P	Roll rate
PLA	Power lever angle
P_s	Specific excess power
PSD	Power Spectral Density
P_{t2}	Total pressure at engine compressor inlet
P_{t6}	Total pressure at engine afterburner
Q	Pitch rate
$\bar{q}$	Dynamic pressure
R	Yaw rate
RF	Range Factor
Rn	Reynolds number
RPM	Revolutions Per Minute
S	Aircraft wing area
SANDS	Standard Analog to Digital System
Sec	Second
S&C	Stability and control
S_g	Ground roll distance
S.M.	Static Margin
SPO	Systems Program Office

SR	Specific Range
t	Time
T_a	Ambient temperature
T/O&L	Takeoff and Landing
TSFC	Thrust Specific Fuel Consumption
T_T	Total temperature
u	Incremental velocity along the longitudinal axis
UFTAS	Uniform Flight Test Analysis System
U_o	Velocity along the longitudinal axis
USAF	United States Air Force
V	Velocity
V_{max}	Maximum attainable velocity
V_{pc}	Position error corrected velocity
V_s	Stall velocity
V_t	True velocity
V_{TO}	Takeoff velocity
V_w	Wind velocity
W	Weight
W_t	Total gross weight
W_f	Fuel flow rate
WUT	Windup Turn
x	Longitudinal displacement
X_{cg}	CG location with respect to mean aerodynamic chord
y	Lateral displacement
z	Vertical displacement

α	Angle of Attack
$\dot{\alpha}$	Angle of Attack rate of change
β	Sideslip angle
$\dot{\beta}$	Sideslip angle rate of change
δ	Pressure ratio
δ_a	Aileron deflection
δ_e	Elevator deflection
δ_r	Rudder deflection
γ	Flight path angle
ϕ	Bank angle
θ	Pitch angle
θ	Temperature ratio
ρ	Air density
μ	Coefficient of friction for tire to runway contact
τ_r	Roll mode time constant
ω_{nd}	Dutch roll natural frequency
ω_{nsp}	Short period natural frequency
ξ_d	Dutch roll damping ratio
ξ_{sp}	Short period damping ratio

CHAPTER I

INTRODUCTION

A. Purpose of the Investigation

Ground testing and flight testing continue to be the only viable methods for a thorough Development, Test and Evaluation (DT&E) program for current aircraft weapons systems. With the advent of super-computers and techniques such as Computational Fluid Dynamics (CFD), simulations of the flight environment are emerging as methods of streamlining the DT&E process. However, for the foreseeable future these computational techniques are relied upon primarily to iterate on the baseline test results, or evaluate the effect of some incremental change to the baseline. This approach inevitably leads again to the reliance upon the ground and flight test results for the absolute proof of acceptability for mission performance. The disparity arises when it is realized that these ground and flight test programs are typically accomplished independently from one another. The ground test phase serving more as a necessary milestone to proceed to the flight test portion, rather than an integral information source, which can be used throughout the flight program. Due to budget and scheduling constraints, this type of independent evaluation can no longer continue.

In this report, the potential benefits of integrating ground test data into the flight test investigations for aircraft performance and flying qualities will be presented. Basic parameters common to both the ground and flight test processes, and invaluable in identifying system characteristics, will be defined to demonstrate how readily the two communities can exchange and compare similar information. In addition, the tools which the flight testers take advantage of during these investigations will be presented to provide the ground test community insight into how their data gets integrated into the flight test program. Most importantly, a technical management plan using the previously discussed analysis tools to integrate the two types of test data into comprehensive system simulations will be presented. This technical approach presented in Figure 1,[1] will serve as an outline throughout this report.

B. Statement of the Problem

During the course of any DT&E cycle, thorough testing, whether it be ground or flight testing, obviously plays an integral role in the maturation of the system. Recognition of this point is evident in Air Force Regulation (AFR) 80-14 [28][2]:

1) DT&E is initiated as early as possible and includes tests of subsystems as well as the total weapon system.

2) DT&E addresses specification requirements as well as expectations that are derived from experience and operational inputs.

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[1]Figures are presented in Appendix A.

[2]Numbers in brackets refer to similarly numbered references in the Bibliography.

3) All systems are evaluated for functional characteristics, integration capability, and simulated failure modes when feasible.

In their article, "The Impact of Concurrent Flight Test and Integrated Ground Testing," Scanlan and Wiles indicated that the cost, schedule and resources required by conventional, independent ground and flight testing programs was becoming too significant to continue [18]. As a result, they recommended a collaboration between the flight test and ground test communities, taking maximum advantage of engineering models to simulate the system. Their basic philosophy involves the generation of a system model, validation of this model by flight test, correlation of discrepancies to improve the model, and finally emulate the flight test cases and extend the flight test results to generate complete handbook information. In their view, the goal of testing in the integrated scenario is to do the following [18]:

1) [Provide] feedback to the development engineering.
2) Provide decision support and contract compliance information to the program manager.
3) Provide capabilities and handbook data to the logistics and operations communities.

These stated goals are essentially rewordings of AFR 80-14, while the method of using engineering models provides an efficient direction with which to proceed.

C. Approach to the Investigation

As presented in Table 1[3], there are a myriad of technical disciplines and resulting interfaces which could potentially be evaluated during the course of the DT&E test program for a typical military aircraft weapon system. The Air Force Flight Test Center (AFFTC), Edwards Air Force Base (AFB) California, is the primary organization in the Air Force responsible for the flight testing of those areas listed in Table 1. Arnold Engineering Development Center (AEDC), Arnold AFB Tennessee, the largest complex of aerospace flight simulation test facilities in the free world, provides the Air Force with the capability to predict the operational characteristics of aircraft systems prior to first flight [29]. Throughout this report there will be continual reference to both the AFFTC and AEDC. The goal to illustrate how efficient integration of information between these two facilities serves to improve the overall DT&E process.

To appreciate this effective integration of information, a small portion of the DT&E process will be analyzed for a typical aircraft weapon system. The two specific areas of the flight vehicle which will be explored are the performance and flying qualities disciplines. Obviously, a thorough understanding of these areas would be a considerable undertaking. As a result, this discussion will be limited to three areas:

[3]Tables are presented in Appendix B.

1) A description of the requirements and results the flight test investigations for performance and flying qualities must meet and provide.

2) The various tools used in the analysis of the flight data for these studies.

3) How these tools can be optimized by relying on the effective integration of the ground and flight test communities.

Subsystems such as stability and control augmentation systems, terrain following systems, weapons separation systems, or engine component improvement programs all would potentially add to the complexity and duration of any test effort. In addition, these highly complex and augmented systems lead naturally into the use of subsystem modeling methods and system simulation techniques, which in themselves add complexity. The basic premise however, is that no matter how complex the system is, an orderly and consistent progression of events must occur for system evaluation. From ground testing of the system, to flight testing, eventual data analysis, and ultimately the simulation updates and application, certain tasks must be accomplished to ensure a thorough evaluation of the system. Also, minimum standards of performance must be satisfied to meet the basic levels of acceptability to the users.

In summary, AFR 80-14 and the Scanlan and Wiles article provide the motivation and direction for the integrated testing approach of this study. Obviously, the need is clear for Military Specification

(Mil Spec) compliance evaluations as well as some type of model generation or system simulation to predict specific performance characteristics. An examination of the tools used to evaluate system performance will concentrate on the methods of evaluation used at the AFFTC. By taking maximum advantage of the system modeling approach, these tools also assist in effectively integrating the ground and flight test data into a single data base or model. Figure 1 presents how this integration might be accomplished for the performance and flying quality evaluations of this study. This representation will serve as the basis for discussion throughout this report. The purpose of each of the major divisions of Figure 1 will be described, as well as their reliance on both the ground and flight data for effectiveness.

D. Organization of Thesis

Chapter II will present the requirements and analysis methods taken into consideration during the integrated ground and flight test performance investigation. The methods used during flight testing at the AFFTC will be discussed to provide an introduction to the ground test community regarding the tools that are used during flight test. In addition, the basic equations which are used for this type of investigation will be discussed as well as how the ground and flight test data should be factored into them.

Chapter III will describe the similar requirements and analysis techniques associated with the integrated flying qualities investigation. For the purposes of this discussion, the flying qualities characteristics of the weapon system can be considered the combination of the stability and control properties of the aircraft, coupled with the handling qualities of the aircraft.

Chapter IV will provide the results of combining the ground and flight data into optimal models of the previously described aircraft characteristics. Errors between the types of data will be evaluated in terms of the impact to the overall mission scenario, and the impact to the operational users.

Chapter V contains the conclusions drawn from the investigation and provides recommendations for ways to improve the integration of the flight and ground test data into an optimal method of evaluating the system.

CHAPTER II

PERFORMANCE REQUIREMENTS AND ANALYSIS METHODS

A. General

As presented in Figure 1, a realistic operational mission simulation should be a major objective of a comprehensive flight test program. In the case of a performance model, the goal is to be able to generate flight manual and/or flight simulator software, which will be representative of the aircraft performance anywhere within the aircraft envelope [16]. This model should be accurate at heavy or light weight, various aircraft configurations or flight conditions. This generalized performance model should be capable of computing performance for any reasonable set of flight conditions, even areas of the envelope where flight test data may not have been obtained. Although great caution would have to be exercised when extrapolation of the model takes place beyond the flight data, good results should be expected when flight test increments are appropriately applied to the predicted data. These types of ground to flight test data comparisons will be made in a subsequent section of this report.

Because of the expense of a comprehensive flight test program, flight test data can usually only cover a sample of the total flight envelope of the aircraft. Therefore, a model which can add flight test increments to the predicted data, serves as an economic way to provide a comprehensive description of the system. As a result, using the predicted data as a baseline for the final model is the primary reason for generating a predicted performance simulation. In addition to this, three other advantages of generating the predicted model are described below. First, it provides engineers with valuable experience in constructing the specific model for the system being investigated. Such front end analysis directly decreases the time required to build the final version after the testing is complete, and time constraints are usually imposed. Time is also saved since the final model usually looks very much like the predicted one. Second, the preliminary model provides an early approximation of the estimated performance characteristics of the system. Once the predicted model is operational, it can provide a guideline for mission planners to prepare for the test program, or even plan each mission. Specific test requirements such as refueling requirements, test point sequence and mission duration can be effectively estimated using a fairly good prediction of aircraft performance. Preliminary safety of flight considerations can also be evaluated using the model. Mission planners and program managers can get a realistic idea of how efficient, productive and safe the test program should be. Finally, the predicted model would allows fast and easy comparisons between the performance of the actual aircraft and the predictions during the test program.

In addition to a realistic operational mission simulation, all military aircraft require a specific performance flight manual. Even prior to any flight testing for a particular aircraft, an interim flight manual must exist which provides a baseline estimate of performance. Since initial mission planning will have to be based on an interim manual, the ground test predictions of the performance of the aircraft must be as representative as possible to the actual aircraft. The Air Force recognizes the fact that predictions are very good estimates at best, but cannot represent the true performance until supplemented with actual flight test results. As a result, according to Air Force Mil Spec standard procedure, when performance data are estimated, fuel flows are increased by five percent. Then when the performance data have been verified by flight test, a conservative factor is not added unless directed by the procuring organization.

Since this conservative approach effects only the prediction for fuel flow, the most direct impact it has is on cruise performance. The Flight Manual presents cruise data in the form of Range Factor versus Mach number. Range Factor (RF) is defined by the following equations [13];

$$RF = \frac{V_t W_t}{W_f}$$

Since; $V_t = 661.48 * M * \theta^{1/2}$,

$W_t = (W_t/\delta) * \delta$,

and $W_f = (W_f/(\delta * \theta^{1/2})) * \delta * \theta^{1/2}$

then,

$$RF = \frac{661.48 * M * (W_t/\delta)}{W_f/(\delta * \theta^{1/2})}.$$

Ignoring Reynolds number effects (i.e., const Rn) and since $(W_t/\delta)/(F_N/\delta) = C_L/C_D$ then;

$$RF = \frac{661.48*M*C_L/C_D}{(TSFC/\theta^{1/2})}$$

where $TSFC = W_f/F_N$.

From this series of equations, it is evident that an error in fuel flow of 5 to 10% would induce errors of from 100 to 500 NAM (Nautical Air Miles), for typical RF values of 2000 to 5000 NAM for a fighter type aircraft. When such errors are introduced into mission planning, obvious fuel shortage implications are apparent.

Although adjustments to the flight manual are applied for fuel flow, other inaccurately predicted parameters may also have significant effects in establishing a performance flight manual. There are a minimum of nine parts to the military performance flight manual. With the exception of only the Introduction (Part 1 of the flight manual), errors in the predicted data will impact every section. The sections are as follows:

Part 1 - Introduction

Part 2 - Engine Data

Part 3 - Takeoff

Part 4 - Climb

Part 5 - Cruise

Part 6 - Endurance

Part 7 - Descent

Part 8 - Approach and Landing

Part 9 - Mission Planning

A brief description of a few of these sections will provide information as to which parameters are most important, and would cause the most problems for the initial flight tests if erroneously predicted data are relied upon.

Part 2 - Engine Data

In the Engine Data Section, the primary information provided in the flight manual is as follows:

a) Maximum thrust available for takeoff,

b) Thrust available in-flight,

c) Fuel Flow and other various engine operating parameters (i.e., Engine Pressure Ratio (EPR), fan speed (N1) and core speed (N2)).

For the performance analysis method presented in this report, the thrust available and fuel flow data act as the primary analysis parameters, since their impact is directly observable in the characteristics being calculated (i.e., range factors and takeoff distances). However, thrust and fuel flow values do rely on parameters such as EPR, N1 and N2. As a result, the effects of these parameters are accounted for in the contractor supplied thrust estimation programs which are an integral part of the flight test data processing.

As discussed, the mandatory fuel flow correction hopefully adds a degree of conservatism to any characteristic which relies on this parameter. However, as presented in the following sections, erroneous thrust terms as well as others will propagate into virtually every area of aircraft performance.

Part 3 - Takeoff

For the Takeoff Section, the most obvious areas of concern are:

a) Takeoff ground run
b) Obstacle clearance distance
c) Takeoff speeds
d) Takeoff gross weight limits
e) Critical field length
f) Takeoff cross wind limits

The remaining seventeen sections of the Takeoff portion either supplement these primary areas or are emergency cases which are variations to these basic cases. The basic takeoff analysis can be divided into two phases, the ground phase and the air phase. The air phase is essentially an accelerating climb to some minimum clearance altitude (50 ft for military aircraft). Since the equations for this phase will be very similar to the nominal climb description in the next section, only the ground phase will be discussed here.

The forces acting on the aircraft during the ground phase are presented in Figure 2 [31]. The equations which describe this situation are presented below:

1) $a_x = (g/W_t)[T_T - \mu W_t - (C_D - \mu C_L)qS - W_t \sin\phi]$ (For average values of T_T, W_t, C_D, C_L, μ and ϕ at .707 V_{TO})

2) $S_g = .0444W_t \ln[(A-BV_w^2)/(A-BV_{TO}^2)] - 1.69V_w t$

where;

$$t = \frac{.026W_t}{(A/B)^{1/2}} \ln \frac{(1+(B/A)^{1/2}+V_{TO})}{(1-(B/A)^{1/2}V_{TO})} \frac{(1-(B/A)^{1/2}+V_w)}{(1+(B/A)^{1/2}V_w)}$$

$$A = (T_T-\mu W_t-\sin\phi)$$

$$B = .00339\sigma S(C_D-\mu C_L)$$

With basic assumptions (i.e.: no runway gradient or wind velocity) these equations simplify drastically; however, our goal is to understand which parameters are the primary variables for takeoff performance. As presented, thrust, lift, drag and tire friction are all parameters which could potentially induce error for the ground roll phase of the takeoff. Of these four, three (thrust, lift and drag) are direct outputs of any thorough ground test program. As will be presented in Chapter IV of this report, errors in these parameters may combine to produce errors of from 20 to 200ft (.5% to 10%) in ground roll distance, or from 20 to 900ft (.5% to 34%) in distance to 50-ft clearance altitude for a representative fighter-type vehicle.

Part 4 - Climb

For the Climb section of the flight manual, the following areas are of paramount concern:

a) Time, Distance and Fuel to climb

b) Combat, Cruise and Service ceiling altitudes

c) Optimum speed to climb

An understanding of the equations describing these properties will also provide information as to the critical parameters for the prediction of climb performance.

The forces acting on the aircraft during the climb are presented in Figure 3 [31]. Summing forces along the thrust line and rearranging terms, yields the following equations:

$$\frac{V(F_N - D)}{W} = V \sin \iota + \frac{VdV}{dt} W.$$

Since

$$\frac{dH}{dt} = V \sin \iota$$

then,

$$\frac{V(F_N - D)}{W} = \frac{dH}{dt} + \frac{VdV}{dt}.$$

Defining the term

$$\frac{V(F_N - D)}{W}$$

as "Specific Excess Power", P_S, then;

$$P_s = \frac{V(F_N - D)}{W} = \frac{dH}{dt} + \frac{VdV}{dt}.$$

This relationship is used extensively during flight tests to define either level flight (dH/dt = 0) acceleration potential, or constant velocity (VdV/dt = 0) climb potential. An important aspect of this relationship is that it takes into account both the potential energy (dH/dt) and kinetic energy (VdV/dt) contributions to the overall energy state of the aircraft. By performing level accelerations this relationship can be used to define a VdV/dt versus velocity curve. Such a curve will define a maximum P_s point at a specific velocity, and in turn define a maximum rate of climb (dH/dt) at that given altitude. A series of accelerations at different altitudes will then define the optimum schedule (i.e., velocity for maximum climb rate) for that specific power setting. Figure 4 presents such a curve. Using P_s as a climb potential (dH/dt) descriptor will also serve to provide the appropriate ceiling information for a particular aircraft. Combat, cruise and service ceilings are defined as the altitudes at which the rate of climb for a specified weight, power and speed are exactly 500 ft/min, 300 ft/min, and 100 ft/min, respectively.

As described, P_s is primarily dependent on knowing the net thrust and drag of the aircraft for the specific flight conditions. It is obvious then, that any predictions of climb performance during the early stages of flight testing, is totally dependent on accurately predicting the thrust and drag levels during ground testing.

From these discussions, it is evident that the basic properties of Lift (C_L), Drag (C_D), Thrust (F_N) and Fuel flow (W_f) are also the critical parameters for the construction of the Performance Flight Manual. This approach tends to simplify the situation, since it does not directly address the various factors which influence the attainment of these specific parameters. For example, thorough studies have been conducted on how to arrive at the installed net thrust (F_N) value, when the value obtained from ground testing is typically closer to the gross thrust (F_G) and measuring F_N directly in-flight is impossible. Also, significant errors to both the ground and flight test calculated results may be introduced because of faulty instrumentation, calibration errors or the myriad of corrections applied to the raw data [35]. As a result, keeping track of the instrumentation status, calibrations and corrections becomes difficult, but essential, bookkeeping exercise for the typical flight test program. Once these potential error sources are eliminated as much as feasible, it is then possible to begin calculating the important performance characteristics such as Specific Range, Max velocity and takeoff ground roll, which is required for operational use.

B. Preflight

As described above, a comprehensive performance simulation requires the integration of both predicted as well as actual test data to arrive at an optimum model. Flight test performance analysis should optimally begin with compiling the predicted data and generating a predicted performance simulation. Although these predicted data are usually generated at facilities such as AEDC, the current practice is for the AFFTC engineers to acquire the data from the primary operating contractor, after obtaining permission from the System Program Office (SPO). This procedure obviously prevents the efficient integration between the ground and flight test communities, since the information is filtered through an extra step of bureaucracy. This situation arises as a direct result of how the USAF acquisition process has evolved. Since the SPO's are responsible for the overall DT&E effort, and AEDC and the AFFTC perform different functions, their support is obtained separately. As a result, the only common technical link between the USAF ground and flight test centers is the primary operating contractor. Ideally, the ground test and flight test information exchanges would be facilitated if AEDC and the AFFTC had the means, and more importantly the permission from the SPO's, to communicate directly with each other regarding their respective results. A means of exchanging information directly between the USAF ground test and flight test organizations at AEDC and the AFFTC should be established to facilitate the overall DT&E effort of the SPO's.

Regardless of how the predicted information is obtained, a predictive model of the performance of the aircraft is the next step in the preflight activities, as presented in Figure 1. The performance model used at the AFFTC for the simulation of in-flight performance is called the Digital Performance Simulation (DPS) [15]. The two basic components of the DPS are the operating characteristics of the engine or propulsion model, and the aerodynamic characteristics of the airframe or aerodynamic model. The propulsion model, at a minimum, consists of a thrust available model and a thrust-fuel flow relationship. The thrust available model is net thrust (F_N) versus flight conditions for the fixed power settings (MIL, MAX, IDLE). The thrust-fuel flow relationship is simply F_N versus fuel flow (W_f) at specific flight conditions. The flight conditions are defined by altitude, ambient temperature and Mach number. The second aspect of the simulation would be the aerodynamic model. This model will at least consist of a drag polar, or drag coefficient (C_D) versus lift coefficient (C_L) at specific Mach numbers. Secondary variables such as Reynolds number (Rn) and center of gravity (CG) position may also be described. The aerodynamic model must also take into account variables such as configuration changes (flaps and gear) and external stores loadings. This model might also include a lift curve, or angle of attack (AOA) versus the same parameters as the drag polar (C_D, C_L, Mach number, Rn and CG). The DPS can easily run specific flight test maneuvers at flight test conditions, such as cruise legs, climbs, accelerations and turns. In addition, some of these maneuvers may be combined to simulate an entire mission profile. The output from the DPS is in the form of the specific performance parameters required in the flight manual, such as range factor, rate of climb, acceleration potential or maximum attainable load factor. These predicted results can then be used to provide preliminary flight manual data, or directly compare to the flight test results for prediction verification. Since the DPS for the predicted data and flight test data are developed in the same manner, the specifics of generating the predicted simulation will be described when the actual flight test generated model is discussed.

As shown in Figure 1, another aspect of the preflight planning is the actual mission planning. To do this efficiently some type of Management Information System (MIS) must be used to lay out the required test points and track their status throughout the program. As specific points are completed, each mission can be planned to accomplish those points which remain. As previously stated, this is one reason the predicted simulation, derived from the ground test data, becomes important. As the specific points are put together to create a mission, the performance characteristics of the aircraft must be understood well enough to know in which order to accomplish the test points; specifically, to take into account requirements such as in-flight refueling and mission duration. With the conservative approach to mission planning which is typically used, a simulation which can predict performance to ±5 to ±10 percent would certainly be sufficient. As will be shown, the estimates which are developed from wind tunnel data are usually at least this good.

Although the Realistic Operational Mission Simulation is presented as a preflight item in Figure 1, at this point it is only as good as the predictions, since the flight testing has not occurred. Based on these predictions however, both the engineering personnel and flight crews should have a very good estimate of aircraft performance. During the Mission Planning stage, the predictions of expected aircraft performance will then be thoroughly discussed as part of any preflight briefing.

C. Flight Test

As presented in Figure 1, two parallel efforts are occurring during the actual flight testing. First, the flight crew is performing the specific set of maneuvers detailed in the approved flight cards. Concurrently, the ground based, or in some cases airborne engineers, are confirming that the maneuvers performed are of acceptable quality to obtain the required data for the specific event. Data displays assist the engineers in assessing the quality of the test points, as well as instrumentation status and safety of flight information. Ensuring stable parameters exist during cruise points, or that the engines are operating as expected during accelerations is essential for accurate results when the data analysis ultimately occurs. Similarly, the flight crew is relied upon to comment on factors affecting each test point, such as aircraft operation or environmental effects such as turbulence. Any event which could potentially effect the results of the test point, must be identified by either the flight crew or the control room team in order to avoid posttest data quality concerns.

During a thorough postflight debriefing, crew comments and engineering observations are consolidated into an accurate Maneuver Event Log so that a point-by-point event log can be constructed which documents the day's testing. In the event log, technical areas of concern as well as qualitative remarks about test point progression are documented. Ideally, when the engineers analyze the data, any inconsistencies between the predictions and the flight data can be resolved on the spot. Conversely, any disagreement between "good" flight test results and the predictions will cast doubt on one or the other sets of data, and more thorough evaluations will be required to resolve the differences. Obviously this situation is an example where an integrated ground and flight test information exchange would pay off.

D. First Generation Data Reduction

The basic data reduction process starts by obtaining time history data of all of the required performance parameters. A sample list is presented in Table 2. To obtain these data, the aircraft is equipped with some type of Integrated Data System (IDS). The IDS provides on-board recording of the measured parameters to an analog tape, while also transmitting real-time telemetry of selected parameters for ground-station monitoring. Upon completion of the flight, the analog tape is converted to digital format using the Standard Analog-to-Digital System (SANDS) processing. The SANDS processing generates output tapes of the Engineering Units (EU) data which are available for the second generation data processing. It also provides a tabular listing of the raw EU data. As presented earlier, a major portion of this step is ensuring data quality by confirming that all of the required instrumentation are accurately calibrated, and that all of the calibrations are correctly applied.

Another aspect of the first generation data reduction phase of the evaluation is to obtain the data required for the takeoff and landing investigation. As presented in Figure 1, a portion of these data are acquired by the Askania phototheodolite cameras located on the Edwards AFB runway. These cameras photograph the aircraft from various angles. A triangulation technique is then used to accurately calculate characteristics such as velocity, acceleration and ground roll distance from brake release. These externally measured parameters are eventually integrated with the onboard aircraft measurements of fuel flow, Power Lever Angle (PLA), elevator position etc., for the complete evaluation [32].

The final item listed as a requirement for the 1st Generation Data Reduction in Figure 1, is the data for the Handling Qualities During Tracking (HQDT) investigation. Since this is a requirement for a Flying qualities evaluation, this topic will be discussed in Chapter III.

E. Second Generation Data Reduction

As presented in Figure 1, The Uniform Flight Test Analysis System (UFTAS) plays an integral role in the data reduction cycle. The UFTAS consists of general purpose software and standard data structures for processing time history data [8]. The standard UFTAS time history data file format is common to the input and output of the various subroutines to allow for standardized handling. Standard software packages exist for time history data reading, smoothing or wild point editing, differentiating and graphical presentation. Project specific packages are developed as required to satisfy the unique requirements of each specific test program. These packages also have the standard time history data format for effective integration into subsequent routines.

In the performance evaluation for a fighter aircraft, the project specific UFTAS will usually contain subroutines to calculate the following:

Pitot-Static Corrections

Test Gross Weight and Center of Gravity (CG)

In-Flight Thrust

Acceleration and Turning Performance

Climb Performance

Cruise Performance

Pitot-Static Corrections

Portions of the first few flights during any DT&E test program are generally devoted to obtaining airspeed calibration data. These data permit making the required pitot-static position error corrections to the airspeed/altitude measuring system of the aircraft. The position error or airspeed system installation error of any test airplane must be determined by flight test for each test aircraft [3]. The static pressure measurement is the primary source of error in this system, since static pressure varies along the fuselage and may not equal free-stream static conditions. As a result, all calculations for airspeed and altitude must be corrected for this instrumentation. Reference [3] explains that four possible sources of the calibration data are currently being used at the AFFTC; Ground Speed Course Method, Tower Fly-by Method, Stabilized Pace Method and Radar Acceleration Method. Other methods used to obtain the correct freestream static pressure are the Trailing Bomb and Trailing Cone. Whichever method is employed, the desired outputs are position error corrections for velocity (V_{pc}), Mach number (M_{pc}), and altitude (H_{pc}). These corrections are applied to the indicated values for velocity, Mach number and altitude and the resulting calibrated values are calculated. Standard atmosphere corrections for compressibility and temperature effects are then applied resulting in the equivalent and true values for these parameters. Once the aircraft specific instrument and position error corrections are identified and input to UFTAS, these same corrections can be applied throughout the flight test program. The procedure for calculating gross weight and CG is similar as far as identifying the baseline parameters at the beginning of the test program and using UFTAS to make these calculations for the remainder of the data reduction.

Test Gross Weight and Center of Gravity

Aircraft empty weight and CG are measured at the AFFTC Weight and Balance Facility at the outset of the flight program. The aircraft is incrementally fueled to calibrate its onboard fuel measuring systems, and new CGs are calculated. In-flight test gross weights are then determined by adding these instrumented fuel quantity readings from each tank to the empty aircraft weight. Empty aircraft moments of inertia are typically supplied by the contractors and are calculated for the in-flight case also using the Gross Weight and CG subroutine in UFTAS.

In-Flight Thrust

Since in-flight thrust cannot actually be measured, it must be calculated based on the measured flight conditions and the best estimate of the operating characteristics of the engine at that flight condition [35]. As a result, the In-flight Thrust Calculation Deck (IFTD) supplied by the engine manufacturer plays an integral role. The IFTD typically requires inputs for the measured test parameters of flight condition (velocity, altitude and temperature), engine pressures, temperatures, fuel flows, rotor speeds and nozzle areas. With these inputs the IFTD can predict gross thrust and ram drag for a specific engine. Inputs from the airframe manufacturer for aircraft specific drag contributors such as the inlet and nozzle are then combined with the ram drag term for total drag. Net thrust along the flight path is then given by the equation:

$$F_N = F_G * \cos\alpha - (F_R + D_P)$$

where:

F_R = Ram Drag

D_P = Sum of Inlet, Nozzle and Environmental Control System (ECS) Drags

This approach relies on the engine and airframe contractor's satisfactory model of the engine and airframe contributions to thrust. As described by Kimzey, Wehofer and Covert in their article "Gas Turbine Engine Performance Determination," this assumption should not be made lightly [35]. As previously discussed, the calculation for F_N is vitally important since it is a critical input into virtually every performance calculation throughout the performance evaluation. As a result, one of the first tests in the flight test program, is the static thrust calibration performed with the engine installed in the aircraft and fixed to thrust cells. The contractor thrust decks can then be verified for the Mach number equal to zero point, and a measure of confidence can be gained. For an extended flight program, this procedure is repeated periodically to evaluate any degradation in engine performance from extended use.

Acceleration and Turning Performance

As previously explained, the specific excess power of the aircraft determines both the climb and acceleration potential [32]. As a result, for high performance aircraft, evaluating level acceleration and climb characteristics go hand-in-hand. For lower performance aircraft a technique called the Sawtooth Climb is employed to determine the optimum climb speed. The name is derived from the barograph trace resulting for a series of climbs through the same altitude. This method is essentially a trial by error method where a series of climbs at slightly different speeds are conducted through the altitude of interest. The predicted optimum climb speed is bracketed and identified. This method is very inefficient for high performance aircraft since many climbs must be performed at slightly different speeds, and climbs at reciprocal headings are required to negate wind effects. The other method of obtaining optimum climb information is the level flight acceleration method. This method serves two purposes. First, it makes available acceleration time and fuel consumption data in level flight at a specific power setting and altitude. Secondly, and more importantly it defines the Specific Excess Power (P_s) characteristics of the aircraft at any velocity throughout the acceleration at the given power setting and altitude. The characteristic plot of P_s vs velocity for various altitudes will then lead to defining the optimum climb schedule for a given power setting [32]. Level accelerations from near min to max-airspeed, performed at various altitudes, power settings (i.e., MIL and MAX) and store loadings will adequately define the P_s characteristics as functions of these variables.

In review, the acceleration method relies on the following relationship for Specific Excess Power;

$$P_s = dH/dt + VdV/dt = V(F_N - D)/W$$

Since net thrust (F_N), drag (D) and weight (W) can all be predicted from ground test data and the manufacturers information, this relationship can be used to predict climb and acceleration performance as a function of velocity, prior to any flight testing. This type of analysis is critical to paper studies of aircraft performance during the design phase of the modern weapon system.

During the turning performance phase of testing, the thrust limitation effects on turning is the primary area of investigation [32]. In stabilized level flight, thrust and drag considerations will be the limiting factors through a large portion of the flight envelope, and for combat flying these parameters also limit turning ability while attempting to maintain constant altitude. The turning performance tests will serve to define the thrust limited turning characteristics at specific power settings as well as P_s characteristics as a function of altitude, Mach number and normal load factor. In addition, these tests will provide the following data for use in the DPS model [13]:

a) F_N/W_f characteristics

b) C_D as a function of C_L and Mach number at relatively high C_L values

In a stabilized level turn, airspeed and altitude remain constant and therefore a review of the P_S equation shows that Ps must be equal to 0 [3]. Since weight can be assumed to be constant over the short period of the turn, the quantity (F_N - D) must be zero in the turn. Also, since high performance turns are performed at elevated power settings (i.e., MIL or MAX power), getting Drag to equal F_N is driven by the increase in induced drag caused by turning at elevated angles of attack. In essence then, any factors which effect Drag or F_N will effect turning performance. For the purpose of this discussion, this means that the DPS model for turning performance will also be a strong function of external store loadings which effect the total aircraft drag. Since the DPS essentially relies on a variation of the basic drag model for each aircraft configuration, it effectively accounts for the addition of aircraft stores.

Climb Performance

Climb performance flight testing usually consists of a series of check climbs to verify the model generated from the cruise and acceleration tests. As previously discussed, this method is used since actually defining the optimum climb schedules by performing climbs is very inefficient. Since climb performance characteristics are a requirement of the Flight Manual, having a valid model verified by actual climbs is a prudent approach.

Cruise Performance

A major portion of any performance flight test program is commonly dedicated to obtaining cruise performance data. These data are used to define Specific Range or Range Factor characteristics as required by the USAF Flight Manuals. Obviously defining range at specific flight conditions and loading configurations is essential to predicting mission capabilities and objectives. This is why this phase of testing has serious implications to contractors and mission planners as they attempt to optimize the final design. The constant W/δ method of testing is the most common technique used to determine the standard day level flight performance of turbojet aircraft [32]. The following parameters are required to make the cruise performance evaluation, and logically become the primary parameters associated with the DPS for the cruise situation:

1. Fuel flow characteristics for store loadings, speeds and altitude conditions.
2. Drag characteristics for all store loadings, speeds and altitude conditions.
3. Specific Range (SR) or Range Factor (RF) characteristics for all aircraft configurations and flight conditions.

The AFFTC performance modeling procedure (using DPS) uses the previously defined equations for Range Factor (RF) to take into account the C_L, C_D, W/δ, W_f and F_N contributions to cruise performance. Once these parameters are effectively modeled, the required flight manual characteristics can be provided throughout the operational envelope.

As presented in Figure 1, after the test day performance characteristics are calculated in UFTAS, these data may be required to be standardized to provide representative values at standard conditions. Standardized atmospheric conditions are used for altitude, air temperature and pressure, while average conditions are frequently used for the aircraft properties (i.e.: aircraft weight and CG corresponding to 50% fuel loading). The following equations provide the test to standard relationship which is used extensively [32]:

$$X_s = X_t + (X'_s - X'_t)$$

where; X = Any parameter being operated on (i.e.: Wf, Fn, RF etc.)

s = Value at standard conditions

t = Value measured at test day conditions

' = Value obtained by modeling method (i.e.: Thrust deck or DPS) rather than measured

This equation relies on the assumption that the model may not be an exact simulation, only that the relative difference between the test and standard values for the parameter are representative. This standardization procedure is used to provide the basis for the Flight Manual, since all values presented there are at standard conditions.

The final aspect of the Second Generation Data Reduction, as presented in Figure 1, is the consolidation of the Takeoff and Landing data base. Range data from the Askania towers and corrected onboard data from UFTAS, are consolidated to provide a comprehensive record. Together, these data sources provide the required information to build the Takeoff and Landing model [1]. For the takeoff and landing situation, a major problem with developing an accurate model is that pilot technique is a significant factor contributing to data scatter [32]. The following factors will all significantly effect either the takeoff or landing results:

1. Speed and sequence of brake and power application.
2. Control surface position throughout the maneuver.
3. Airspeed at rotation or during flare.
4. Pitch rate during rotation or flare.
5. Angle of attack during lift-off or flare.
6. Braking technique.

Since these variables may have significant impacts on the results from point to point, large data scatter and low repeatability are common. Indepth preflight briefings on standardized techniques, as well as a large number of data points are common practice to accurately model these terminal flight phases. Once pilot technique is minimized as much as possible, through briefings on standardized techniques and practice, the data can be gathered with better confidence. Data on gross weight, ground roll distances, accelerations, velocities, temperatures, winds, power setting, and engine characteristics are typical information required for the model. The merging of the range and onboard data is essential to provide the total picture for the specific test point.

F. First Generation Data Analysis

Early in the preparation phase of any test program, a decision is made as to how indepth the data analysis is to be done. Depending on the specific requirements of the program, a cursory verification of the performance predictions may be performed, or a detailed evaluation and characterization of the system may be required. The conventional analysis methods represented in Figure 1, rely on basic performance relationships and extensive plotting and crossplotting of the results to obtain the desired outputs for RF, SR optimum cruise Mach number, etc. The detailed method of this type of analysis as taught at the USAF Test Pilot School, Edwards Air Force Base, California is presented in Reference [32]. Becasue of the labor intensive nature of this technique, the results are typically so specific that they are of limited use in developing the complete flight manual. These results are most applicable to cursory checks of predictions, as well as Mil Spec compliance analysis for very specific cases at specific flight conditions (i.e.: max cruise range, max attainable velocity or min takeoff distances).

The technical merits of these classical techniques are obviously sound, and provide the basis for understanding the theory and applicability of any performance analysis. However, the generation of a performance model results in the definition of baseline aircraft and engine performance characteristics, allowing flexible application of the technique to a variety of situations [27]. Direct use of the model for simulations of various flight maneuvers and conditions as well as correlation of wind tunnel results can all be simple operations once an accurate model exists. As a result, the standard method of performance analysis at the AFFTC relies on creating a performance model of the system [16]. The specific tool which is used for this purpose was developed by Wayne M. Olson, and has evolved into the Digital Performance Simulation (DPS) [15]. The basic premise is that any aircraft performance capability (i.e., RF, max range etc.) can be determined by reliance upon demonstrated performance characteristics. The DPS relies on the characterization of aircraft lift, drag, thrust and fuel flow obtained during various aircraft maneuvers or predictions to provide the data base which is modeled. The standard procedure is to utilize a nonlinear regression procedure as a mathematical tool to model the lift, drag and fuel flow characteristics [16]. As presented in Figure 1, the first step in developing the DPS is the modeling of the lift, drag and fuel flow with the nonlinear regression.

References [14] and [16] contain descriptions of the DPS and provide the basic objectives and theory behind the procedure. Critical to the model development is the use of a nonlinear regression analysis to provide three subroutines which characterize the aircraft performance. The first user developed subroutine is the drag and angle of attack (AOA) routine which provides C_D and AOA from primarily C_L, M, T_a and δ. Other inputs such as gear and flap settings or store loading may require separate models and are provided as required. The second suboutine is a thrust and fuel flow characterization which provides F_G, F_E and W_f from power setting, AOA, M, δ, and θ. For the cruise condition, F_N is also an input since F_N = Drag. The final user requirement is a subroutine for maximum C_L, which provides $C_{L_{max}}$ and $N_{Z_{max}}$ from an input of Mach number. Relying on only these three subroutines to characterize the performance of the system is consistent with Olson's philosophy to keep the model as simple as possible [16]. It should be remembered however, that secondary parameters such as EPR and compressor speeds are important to the propulsion aspects of the system, and are included in the model provided by the engine contractor in the IFTD, which is an integral part of UFTAS.

Once the three aircraft specific subroutines have been developed (i.e.: the parameters of primary importance have been modeled), the DPS can be consolidated and implemented. References [15] and [7] provide the detailed descriptions regarding the incorporation of the user supplied subroutines, the specific capabilities of the model and actually running the program. As presented in Figure 1, the DPS has basically two modes, the Mission Simulation mode and the Maneuver (Non-mission) Simulation. In the Mission mode, the DPS will compute time, distance and fuel used to perform any combination of eleven specific maneuvers. This tool is obviously handy for either mission planning or predicting duration and fuel usage requirements for simulated missions. As previously discussed, since the DPS relies on parameters available from either the ground or flight test data, it can be generated prior to flight. This fact provides significant capability to the acquisition community.

In the Maneuver Simulation mode, ten of the same Mission maneuvers and one additional can be run independently. This method provides data appropriate for fairings through flight or ground test data bases as opposed to the time-distance-fuel information provided by the Mission simulation. An example is a constant altitude cruise maneuver both in the Mission and Non-mission modes. The Non-mission option provides RF vs Mach number data at a specified constant weight, while the Mission option keeps Mach number constant and calculates distance, time and fuel used throughout the maneuver until a specified end weight is achieved [15].

The twelve maneuvers which are possible are as follows: Four types of wing level climbs, three types of cruise maneuvers, two types of turns, an acceleration, a terrain following sequence and a P_s contour maneuver [14,15]. The four types of climbs are: 1) a constant calibrated airspeed/Mach number climb, 2) a constant equivalent airspeed/Mach number climb, 3) a constant normal load factor climb (pull-up) and 4) a constant pitch attitude climb. The three types of cruise legs are: 1) a constant altitude cruise, 2) a constant weight-pressure ratio (W/δ) cruise which not possible in the Non-mission mode, and 3) a maximum speed cruise where $F_{ex} = 0$. The turns are a constant specific excess power (P_s) turn and a lift limited turn. Both turns are at constant altitude. The acceleration assumes constant altitude and constant normal load factor. Descents and decelerations are performed by specifying negative increments to altitude or Mach number during a climb or acceleration. As a result, these maneuvers are not considered unique. The terrain-following option is constant Mach number maneuver assuming an x,y,z terrain history is available, as well as min and max allowable values for normal load factor and power setting. The twelfth maneuver is strictly a data plotting tool (Non-mission) to provide contours of constant P_s as a function of Mach number and altitude.

A similar philosophy as applied to the in-flight performance analysis, is applied to the takeoff and landing (T/O&L) data. As presented in Section A of this chapter, the governing equations for the takeoff situation are relatively tedious, especially when the appropriate corrections are applied to obtain the sea-level standard conditions required of the flight manual [32]. As a result, a T/O&L performance model is desirable which provides the same flexibility as the DPS for the in-flight analysis. The model which is used at the AFFTC for this T/O&L analysis has been developed from computer programs designed by NASA Ames Research Center [1]. These programs have been converted to operate on the AFFTC computer system, and Reference [17] provides the supplemental information for its use.

As discussed, this program has a similar role for T/O&L as the DPS has for in-flight performance. Ideally, this model is also developed from predicted data, then updated from flight test data to more accurately reflect the actual T/O&L performance characteristics. Both programs require user supplied thrust and drag subroutines, and can be used to simulate test day or standard day maneuvers. In the T/O&L

case, the thrust and drag subroutines are commonly derived from the in-flight data, with corrections for ground effect, and the resulting model is used to simulate the actual flight test results. If the simulation for these cases is accurate, the model can be used to estimate the standard day performance. Since the aircraft is treated as a point mass confined to motion in the vertical plane, the program is applicable to conventional, vectored lift and powered-lift concept aircraft [1].

The AMES documentation defines three standard, non-user supplied subroutines as TAKEOFF, LANDING and ZERO [1]. These provide the appropriate terminal flight phase equations, as well as the required values of thrust and AOA for zero acceleration during the approach to landing phase. As described earlier, the two user supplied subroutines are similar to the thrust and drag subroutines required by DPS. In the T/O&L model they are designated ARODYN and ENGINE [1]. Subroutine ARODYN computes the total force coefficients along, and normal to the flight path as functions of AOA, dynamic pressure, thrust, thrust vector angle, aircraft configuration and atmospheric condition. Subroutine ENGINE provides the appropriate propulsion data as a function of altitude, temperature, Mach number, power setting and fuel flow.

For calculation purposes, the takeoff maneuver is divided into four basic segments: ground roll and rotation, lift-off and initial segment climb, acceleration to final climb speed at a constant rate of climb, and finally, the pullup maneuver to establish the final climb speed [1]. Provisions in the program are made for the following:

rotation limited by a specified tail scrape angle, gear retraction, flap retraction, changing of vectored thrust angle and changes in power setting. Specific details of each of the four segments and options available for each are detailed in Reference [1]. It is important to note however, that the final climb segment is a logical starting point for the DPS to be used to initiate a complete mission simulation.

The landing maneuver is divided into three distinct phases: the approach, the flare to touchdown, and the rollout [1]. The approach is made at the thrust and AOA required for zero acceleration along and normal to the flight path. These values of thrust and AOA for steady state approach may either be input by the user or calculated in subroutine ZERO. The flare is executed by increasing AOA at a specified rate to either a specified limit, or tail scrape angle whichever is less. After touchdown, the rollout is then executed, with provisions for any pilot reaction delay time in brake application, spoiler deployment or thrust reversal. The landing run terminates when the aircraft comes to rest.

Once this T/O&L model has been developed from either the predicted or flight test data bases, it can provide the required takeoff acceleration rate and distance versus speed and weight data required of the flight manual. In addition, significant flexibility is available with relatively little effort. The following two examples provide actual circumstances where the flexibility of this type of model demonstrated its potential. First, using purely predicted data, a program office was able to evaluate the T/O&L performance increments available from re-engining an operational aircraft. Once the new engine characteristics were predicted and input to the program, various conditions of aircraft weight and atmospheric condition were evaluated using the proposed engine-aircraft combination. As a result of the significant improvement in takeoff performance, the USAF approved this re-engine program for this model of aircraft. The second example involves a safety of flight application where a variable sweep aircraft was required to land with its wings fully swept aft. During a routine training flight, a mechanical malfunction froze the wings of an aircraft in the high speed, fully swept configuration. The aircraft requested diversion to Edwards AFB for an emergency lakebed landing. Since a T/O&L model had been developed for the standard landing configuration (i.e., wings swept forward), and the DPS model had aerodynamic definitions for all in-flight cases, engineers elected to merge the data bases to evaluate the emergency situation. Prior to the arrival of the aircraft at Edwards, the model predicted that even with the wings swept, it could safely land on the concrete runway. As a result, a landing on the runway was attempted and safely executed. Both of these examples demonstrate the flexibility in application of an existing model. In both of these cases the flight manuals were of little value since these situations were so extremely nonstandard. These cases demonstrate that the development of system models, first based on predictions then updated by actual flight test data, should be the standard analysis procedure for any evaluation.

G. Second Generation Data Analysis

Based on the results of the integration of the ground and flight test data, it is now appropriate to recommend any required flight manual revisions and verify Mil Spec compliance. As stated earlier, depending on whether or not a model was developed, this process can be either a limited point by point comparison against Mil Specs, or a thorough, comprehensive redefinition of the initially predicted characteristics. Basically, if the modeling philosophy was carried on throughout the evaluation, it is now possible to update the simulations rather than simply identifying errors in specific regions. The updated simulation should now be capable of providing the most realistic simulation for any operational application. Figure 1 also demonstrates an important iterative testing capability, assuming close coordination is maintained between the ground and flight test communities. If an accurate model of the system exists, engineers can evaluate whether or not the system performs in an environment of changing expectations or requirements. Assuming some specific deficiency exists (i.e.: as in the previous case of less than desired takeoff performance), then the ground test team can evaluate an alternate subsystem, and incorporate these characteristics into the system model. If the new system model demonstrates the desired capability, then a limited flight test program may be undertaken to verify the predictions. Another case may be the situation whereby the basic system simply cannot perform up to expectations or changing requirements. After all variations to the baseline model have been exhausted, a new concept may have to be explored and the iterative ground and flight testing process would have to start again. In summary, the combination of the team approach to the ground and flight test evaluations, along with reliance on a constantly updated simulation, can provide program managers and engineers with the most accurate information with regard to system performance and capability. This team approach with the reliance upon system modeling should be the standard operating philosophy whenever a major weapon system is being developed.

CHAPTER III

FLYING QUALITIES REQUIREMENTS AND ANALYSIS METHODS

A. General

The Mil Spec for the flying qualities of piloted airplanes, is intended to assure flying qualities that provide adequate operational mission performance and flight safety. At this point it is appropriate to define the various aspects of the term "flying qualities". The flying qualities of the aircraft consist of the aircraft stability and control characteristics, as well as the aircraft handling qualities [30]. The stability and control characteristics may be defined as the quantitative measurements which describe the flying qualities of the aircraft. The handling qualities are described by the pilot's qualitative assessment of his ability to perform specific tasks in the aircraft. Both the stability and control properties and handling qualities must be combined to fully define the flying qualities of the aircraft. The existence of the Mil Spec which defines levels of acceptable flying qualities in terms of both quantitative and qualitative measures, is evidence of this combined approach. The specification requires the evaluation versus specific standards, as well as qualitative descriptions of the demonstrated flying qualities for all aspects of the mission. The following is a partial list of the areas requiring evaluation:

1. Longitudinal Flying Qualities
    a. Stability with respect to speed

b. Maneuvering stability characteristics

c. Longitudinal control

2. Lateral-Directional Flying Qualities

a. Mode characteristics (i.e.. Dutch Roll, Spiral, etc.)

b. Dynamic response characteristics

c. Roll control effectiveness

3. Miscellaneous Flying Qualities

a. Flight at high AOA (i.e., Buffet, Stall, etc.)

b. Effects of releasing stores

Although this is not an all-inclusive list, an introduction to the evaluation of the stability and control (S&C) characteristics in each of these areas will provide insight into the applicability of a coordinated ground and flight test effort. References [30] and [33], the AFFTC reference document for flying qualities and the USAF Test Pilot School text, both provide the indepth theory and step by step techniques for evaluating these qualitative characteristics [30,33]. What they do not emphasize is the importance of evaluating the combined qualitative and quantitative performance of the system. A simulation of the system serves as an ideal tool with which to perform this type of evaluation. The Mil Spec recognizes this for certain cases by requiring a piloted simulation before the first flight of a new airplane design to demonstrate the suitability of the handling qualities. In addition, when a simulation is the ultimate method of demonstrating compliance for a requirement, the simulation model shall be validated with flight test data. In summary then, not only is it desirable, it is required for certain cases that the philosophy discussed in Chapter II of this report be followed. That is, the development of a predicted model of the system be generated from ground test data, and eventually validated or updated with flight test data to provide the most accurate representation possible. It is important to realize that those cases which do not fall under these specified cases, can also benefit from this emphasis on an accurate, continuously updated simulation. A review of the basic aerodynamic principles and the tools used for their application, will demonstrate the advantage that a closely coordinated flight and ground test program can have on the evaluation of the flying qualities of the aircraft.

In the performance analysis section of this report, parameters such as lift, drag, thrust and fuel flow were shown to provide essential information about the aircraft. When these parameters were manipulated with certain other basic data, they could define the aircraft performance throughout the envelope. The definition of these basic parameters was convenient since they were attainable both during the ground test and flight test phases, and direct comparisons and integration into the simulation were possible. With the advent of highly automated data acquisition systems, and large capacity, high speed digital computers to solve complicated algorithms, it was possible in the mid-1960's to define these same type of parameters for the S&C application [30]. The resulting stability coefficients and derivatives serve the same function for the S&C analysis as the lift and drag data do for the performance analysis. The following discussion describes how these parameters serve to define the S&C characteristics of the aircraft and how they are used to evaluate the specification requirements.

As presented in Reference [30], the total aircraft motion can be thought of as two independent motions, resulting in stability coefficients and derivatives defined as either longitudinal or lateral-directional. These derivatives and related parameters which serve to define the basic coefficients are as follows:

Longitudinal;

$$C_D = C_{D_o} + C_{D_u} * u + C_{D_\alpha} * \alpha + C_{D_{\dot\alpha}} * \dot\alpha + C_{D_q} * q + C_{D_{\delta e}} * \delta e$$

$$C_L = C_{L_o} + C_{L_u} * u + C_{L_\alpha} * \alpha + C_{L_{\dot\alpha}} * \dot\alpha + C_{L_q} * q + C_{L_{\delta e}} * \delta e$$

$$C_m = C_{mo} + C_{mu} * u + C_{m_{\dot\alpha}} * + C_{m_{\dot\alpha}} * \dot\alpha + C_{mq} * q + C_{m_{\delta e}} * \delta e$$

Lateral-Directional;

$$C_y = C_{y\beta} * \beta + C_{y\beta} * \beta + C_{yp} * p + C_{yr} * r + C_{y\delta a} * \delta a + C_{y\delta r} * \delta r$$

$$C_l = C_{l\beta} * \beta + C_{l\beta} * \beta + C_{lp} * p + C_{lr} * r + C_{l\delta a} * \delta a + C_{l\delta r} * \delta r$$

$$C_n = C_{n\beta} * \beta + C_{n\beta} * \beta + C_{np} * p + C_{nr} * r + C_{n\delta a} * \delta a + C_{n\delta r} * \delta r$$

For each type of motion, these derivatives may be divided into "stability" derivatives which describe the natural tendency to return to trim when disturbed, force derivatives, control surface derivatives, damping derivatives and lag or unsteady flow derivatives.

"Stability" Derivatives;

Longitudinal - C_{mu}, $C_{m\alpha}$

Lateral-Directional - $C_{l\beta}$, $C_{n\beta}$

Force Derivatives;

Longitudinal - C_{Du}, $C_{D\alpha}$, C_{Lu}, $C_{L\alpha}$

Lateral-Directional - $C_{y\beta}$

Control Surface Derivatives;

Longitudinal - $C_{D\delta e}$, $C_{L\delta e}$, $C_{m\delta e}$

Lateral-Directional - $C_{y\delta a}$, $C_{y\delta r}$, $C_{l\delta a}$, $C_{l\delta r}$, $C_{n\delta a}$, $C_{n\delta r}$

Damping Derivatives;

Longitudinal - C_{Dq}, C_{Lq}, C_{mq}

Lateral-Directional - C_{yp}, C_{yr}, C_{lp}, C_{lr}, C_{np}, C_{nr}

Unsteady Flow Derivatives;

Longitudinal - $C_{D\dot{\alpha}}$, $C_{L\dot{\alpha}}$, $C_{m\dot{\alpha}}$

Lateral-Directional - $C_{y\beta}$, $C_{l\beta}$, $C_{n\beta}$

The unsteady flow derivatives, which are functions of $\dot{\alpha}$ and β, cannot be distinguished from pitch rate or yaw rate (q and r) in either the wind tunnel or in flight. Therefore, the damping derivatives which are functions of q and r also contain the lag effects for $\dot{\alpha}$ and β, respectively [30]. In addition, any cross-sectional derivative effects are neglected to simplify the two motion analysis approach.

Assuming the total aircraft motion occurs as either a longitudinal or lateral-directional motion, the overall S&C problem is reduced to specific parameters in specific equations. As in the case of the performance study, it is now possible to define the S&C characteristics throughout the envelope using these defined parameters. Since however, these derivatives are defined by linear relationships of one parameter to another, non-linear characteristics (i.e., departures from controlled flight) will not be reflected by simply extrapolation of these derivatives. This is consistent with the performance philosophy of being extremely careful when attempting to predict the true characteristics by extrapolating beyond the data base.

It is now appropriate to discuss how these derivatives can be used to evaluate the following areas of interest defined by the specifications:

Longitudinal Flying Qualities

Lateral-Directional Flying Qualities

Miscellaneous Flying Qualities

Longitudinal Flying Qualities

The initial requirement of longitudinal flying qualities acceptability is the need for stability with respect to speed. According to the Mil Spec, this requires that the pitch controller deflection and force increment required to maintain straight and level flight at a different speed, are in the same direction as required to initiate the speed change; that is airplane-nose-down control to fly at a faster speed, airplane-nose-up control to fly at a slower speed. Other than plotting stick force versus velocity, and identifying smooth gradients on such plots, further quantification of these characteristics is not required. The longitudinal control requirements are developed in essentially the same way. For 1g (load factor or n equal to 1) and maneuvering flight (load factor or n not equal to 1), speeds and load factors between V_s to V_{max} and nmin to n_{max} respectively, must be attainable with the available pitch control. By simply plotting the exhibited values of F_s/n (Stick force/g) versus n/α the specification can be verified. Obviously this approach applies equally well to either the manned simulator or the flight test vehicle.

Although not specifically required by the Mil Spec, an understanding of the neutral point, static margin and maneuver point are all helpful in characterizing the flying qualities of the aircraft. These characteristics provide information about the longitudinal static and maneuvering response to disturbances. The neutral point (h_n) is defined as the CG location where the aircraft displays neutral static stability, or $C_{m\alpha}/C_{L\alpha} = 0$ [30]. Then $h_n = X_{cg} - C_{m\alpha}/C_{L\alpha}$, where X_{cg} = CG/c. The static margin (S.M.) is then defined as;

$$S.M. = - C_{m\alpha}/C_{L\alpha} = h_n - X_{cg}.$$

If S.M. > 0 then the aircraft exhibits positive stability, whereas if S.M. < 0 then negative stability exists. The maneuver point (h_n) is defined as the CG location where $dF_s/dn = d\delta e/dn = C_{mq} = 0$. Reference [30] describes the theoretical development of this characteristic, and that the CG location may be different in low g turns vs low g pull ups because of the aircraft orientation. As a result,

$$h_{n_{pull}} = h_n - \frac{C_{mq} * \rho * S * c * q}{4 * W}$$

$$h_{n_{turn}} = h_n - \frac{C_{mq} * \rho * S * c * q}{4 * W} \left(1 + 1/n^2\right)$$

Whether the pullup or turn equation is applied, the important point is that the definition of specific stability derivatives in the wind tunnel or from flight, should play a crucial role in evaluating the longitudinal static stability of the aircraft.

Another major area of investigation for the longitudinal case, is the evaluation of the longitudinal maneuvering characteristics. This evaluation provides an assessment of the short period response and control feel characteristics during maneuvers. The method for evaluating the response characteristics involves defining the short-period undamped natural frequency, w_{nsp}, and short-period damping ratio, C_{sp}. The w_{nsp} properties are demonstrated by plotting w_{nsp} versus the ratio of n/α, and ensuring they fall within specified limits. The damping ratio (C_{sp}) is also required to fall between certain minimum and maximum allowable levels, depending on the specific flight phase (i.e., air-to-air combat, cruise, takeoff, etc.).

References [11], [19], and [30] present the theoretical derivations and at least five different methods of calculating the response characteristics from the demonstrated response to standard control inputs on the aircraft or simulator. Since it is important to recognize a method consistent with both the ground and flight test derived data, the following equations apply [19,30]:

$$\omega_{nsp} = [-(q*S*c/I_{yy})*C_{m\alpha}]^{1/2}$$

$$n/\alpha = (C_{L\alpha}*q*S)/W$$

and,

$$\xi_{sp} = \frac{-q*S}{2*w_{nsp}*U_o} * \frac{[\xi^2*C_{mq}}{[2*I_{yy}} - \frac{(C_{L\alpha} + C_{Do})]}{m \quad]}$$

or

$$= \frac{(M_q + Z_\alpha/U_o)}{2*w_{nsp}}$$

where,

$$M_q = \frac{q*S*c^2 + C_{mq}}{2*I_{yy}*U_o}$$

$$Z_\alpha = \frac{q*S*q*C_{N\alpha}}{W}$$

In summary, a relatively detailed understanding of the longitudinal S&C characteristics is possible by simply defining in either ground or flight test, the appropriate stability coefficients which act as the primary drivers for the specific property being investigated (i.e.. h_n, S.M. or ω_{nsp}). The objective of this discussion has been threefold: 1) to introduce stability coefficients as the basic parameters describing longitudinal motion, 2) to provide the ground work for describing how they are obtained and evaluated during the flight test program, and 3) to demonstrate that assuming the most accurate values of these parameters are achieved from the ground test data, it is possible to compare these results with the flight test data and generate an accurate model of the system.

Lateral-Directional Flying Qualities

Evaluation of the lateral-directional flying qualities is more complicated than the longitudinal case, since a disturbance in either the lateral or directional plane will result in a "cross-coupling" effect which initiates motion in the other plane [30]. As a result, an area of primary interest in the specification is the characterization of how the different motions interact. The evaluation of Dutch Roll, Pure Roll and Spiral Modes of the aircraft motion provides this information.

Dutch Roll oscillations involve combined roll, yaw and sideslip motion. The stability characteristics of these oscillations are described by defining the frequency (ω_{nd}), damping ratio (ξ_d), and bank angle to sideslip angle ratio (ϕ/β). Obviously the frequency and damping characteristics have a significant effect on the aircraft's Dutch Roll response of the aircraft to small disturbances. Minimizing this dynamic response to small disturbances is critical to improving the ability of the aircraft to perform certain tasks, such as aiming during bombing runs, gun or rocket firings and precise formation flying such as in-flight refueling. Specifications identify specific criteria for the frequency, damping ratio and ϕ/β properties for the various flight phases. As in the longitudinal case however, there are various methods of deriving these properties for specification comparison. For our purposes, using the stability coefficients available from the ground and flight test evaluations offers the most compatibility with the integrated approach. The following approximating equations apply [25,30]:

$$\omega_n = [((q*S*b)/I_{zz})*C_{n\beta}]^{1/2}$$

$$\xi_{nd} = \frac{-\rho*U_o*S*b^2*C_{nr}}{4*I_{zz}*\omega_n} = \frac{-C_{nr}}{8}\left|\frac{2*S*b^3*\rho}{I_{zz}C_{n\beta}}\right|^{1/2}$$

$$\left|\frac{\phi}{\beta}\right|_d = \frac{C_{1\beta}*I_{zz}}{C_{n\beta}*I_{xx}*(1+1/\omega_n^2*\tau_r^{\ 2}))}$$

where τ_r is defined as the "roll mode time constant" whose equation is;

$$\tau_r = \left|\frac{4*I_{xx}}{C_{1p}*\rho*U_o*S*b^2}\right|$$

The Roll Mode represents the non-oscillatory response to the pilot's lateral stick input which involves almost pure roll [30]. Identifying the characteristics of the roll mode is important in defining how maneuverable the aircraft is. The roll mode time constant (τ_r) is that time for which the aircraft has reached 63% of its maximum steady state roll rate following a step input of lateral control. In addition to the frequency, damping and ϕ/β parameters, the roll mode time constant must also meet certain specifications. The roll control of the aircraft is directly related to τ_r since it is defined as the amount of bank angle change possible in a given time [30]. This roll performance must be demonstrated in-flight or by a manned simulator to meet specified levels.

Miscellaneous Flying Qualities

In the evaluations of high AOA and flying qualities during the release of stores, qualitative rather than quantitative assessments are performed. Phrases such as "adequate stall warning or buffet", "adequate pitch control for recovery" and "no uncontrollable departures", are all typically used during these evaluations. Because high AOA testing is inherently dangerous, it is important to maintain an accurate simulator which can be used to introduce the pilot to the expected characteristics.

In summary, similar to the performance analysis, once the basic parameters which describe the S&C characteristics are defined, it is possible to provide the necessary inputs to the flight manual or system simulation. In the S&C case, it is evident that these basic parameters are the stability derivatives which are used to develop a complete analytical description of the system. Now it is possible to describe how these derivatives are derived and applied throughout the flight test program.

B. Preflight

As previously discussed and presented in Figure 1, an accurate flying qualities simulation requires the integration of both predicted as well as flight test data. Like the performance analysis therefore, the flying qualities investigation should begin by generating a predicted model or simulation based on the ground test data. The predicted flying qualities simulation can take several forms. The two primary tools available at the AFFTC are the real time simulator and the Environmental Control Analysis System 5 (EASY5) computer simulation program [20, 21]. The real time simulator, either man-in-the-loop or programmed input, is developed from the stability equation relationships. It has the capability for high speed, high volume time and limited frequency domain analysis. This simulation may be used for the following tasks [21]:

- Limit cycle studies (for new or modified control systems)
- High AOA studies
- Parametric studies
- Failure state studies
- Envelope expansion or critical maneuver identification
- Flight planning
- Pilot or engineer training and familiarization
- In-flight problem evaluation and solution verification
- Turbulence studies
- Standardization of flight test data

The EASY simulation is developed from detailed block diagrams of the system and does require large amounts of computer time to run a specific case. It is however, the primary tool for obtaining frequency domain information (i.e., transfer function relationships). In addition the following capabilities exist [21]:

- Time history information
- Direct model versus flight test response comparison

- Standardization of flight test data
- Characteristic equation pole and zero data for root locus a analysis

The specific requirements for generating the simulators will be discussed in a later section, however it is appropriate to identify the real time simulator as the primary tool in the preflight stage of the evaluation. This is because it satisfies most of the preflight requirements, is relatively easy to develop, and is based on the predicted equations of motion and associated stability derivatives which can be directly compared to the flight test results.

The development of a real time of simulator is critical for certain types of flying qualities evaluations. High AOA studies or testing aircraft with newly designed, highly automated flight control systems (i.e., X-29 or AFTI F-16), are inherently dangerous and demand such preflight studies. Because of the identified capabilities however, the development of such simulations should be the normal procedure for routine DT&E efforts rather than an afterthought. The capability to constantly update the fidelity of the simulation also needs to be built into the process. This effort certainly requires close coordination between the flight and ground test communities. For the USAF application, this process would be improved if a means of exchanging information directly between the USAF ground test and flight test organizations at AEDC and the AFFTC were established. Although this recommendation is restated from the performance section, it applies equally well for the flying qualities analysis.

As presented in Figure 1, the remaining activities required for the preflight test phase is the maintenance of some type of management information system (MIS), and the mission planning functions. The MIS functions are identical to those identified for the performance investigations, that is to lay out all of the required test points for the program, and track the status of these points throughout the program.

Because of the pilot technique dependent nature of most flying qualities maneuvers, as compared to performance maneuvers, the simulator typically plays a vital role in the mission planning phase. Maneuvers such as wind-up turns (WUTs), pitch and roll doublets, and roll performance step inputs, are so pilot dependent that the ability to practice these maneuvers in the simulator, has the potential to save valuable time and material resources throughout the program. Although these maneuvers are introduced at the USAF Test Pilot School, every aircraft is unique and understanding the differences prior to flight may be crucial. Familiarization of the pilot and engineers to the expected handling characteristics of the specific aircraft, is also critical in avoiding potentially dangerous flight conditions which might otherwise be inadvertently encountered during the mission. The degree to which the engineering team utilizes the simulator obviously depends on the known aircraft characteristics and the expected flight profile. In extreme cases, such as the Advanced Fighter Technology Integration F-16 (AFTI F-16), with very unique flight control systems and handling characteristics, virtually every test point for every mission profile would be flown in the simulator prior to the actual mission. The reliance on an accurate, high fidelity simulation for these applications is obvious, as is the requirement for continual ground and flight test data exchange throughout the program.

C. Flight Test

As in the performance study, parallel activities are occurring during the actual flight testing. While the flight crew is performing predetermined maneuvers, the engineering team is evaluating the appropriate real-time data displays and approving the point-by-point progression through the mission. As described, since the maneuvers required for the data analysis in the flying qualities evaluation are so pilot technique dependent, close coordination during this phase is essential. The longitudinal and lateral-directional doublet maneuvers required for accurate stability derivative extraction are so critical, that the engineers must closely monitor the pilot's technique for control inputs during these tests [12]. In addition, smooth control stick inputs during wind-up turns are required to accurately plot the F_s/g data required of the Mil Specs. This sounds simple enough, but when the pilot is required to smoothly increase load factor from 1g to 6 or 7gs, in clouds, turbulence or limited airspace, patience and coordination between the flight crew and ground team is essential. Any of the of in-flight conditions which may effect data quality must be appropriately documented for evaluation during the post-test data analysis.

Compilation of a complete and accurate post-test Maneuver Event Log is crucial to the overall assessment of the data quality and demonstrated flight characteristics. Inconsistencies between predicted and flight test data bases may be resolved based upon in-flight problems or environmental effects. Conversely, if the flight test data is considered accurate, further coordination and refinement of the predictions may be warranted. As in the performance case, this is facilitated with an open line of communication between the ground test and flight test organizations. In addition to identifying factors which may contaminate the data (i.e., sluggish control inputs or excessive turbulence), the Maneuver Event Log documents those characteristics which are only evaluated based on the qualitative assessment of the test team. Flight manual descriptions of characteristics demonstrated during maneuvers such as approach to stall (i.e., buffet or wing rock), or precise tracking tasks (i.e., refueling or formation flying) are totally dependent on the test team's qualitative assessment and thorough documentation of these characteristics.

D. First Generation Data Reduction

The required flying qualities time history data are obtained in the same manner as the performance data. Although certain parameter sets may be selected for different mission phases, the onboard Integrated Data System (IDS) is maintained to support all required instrumentation. A sample list of flying qualities instrumentation parameters is presented in Table 3. The procedure for converting the raw IDS data tape into EU through the SANDS processing is identical for both the performance and flying qualities efforts. A significant amount of effort is again required for instrumentation calibration and correctly applying these calibrations to the measured parameters.

As presented in Figure 1, Handling Qualities During Tracking (HQDT) data are one source of information used to evaluate the overall handling qualities of the aircraft. The following definitions serve to illustrate the handling qualities problem [23]:

> Pilot - A set of nonlinear, nonstationary dynamics we don't fully understand.
>
> Stability and Control - The static and dynamic characteristics of the airplane.
>
> Handling Qualities - Closed-loop interaction between the dynamic characteristics of the airplane and the dynamic characteristics of the pilot.
>
> Stability and Control Testing - Tests which measure the static and dynamic characteristics of the airplane (i.e.: pulses, doublets, time to bank).
>
> Handling Qualities Testing - Pilot-in-the-loop tests to measure how well the pilot dynamics interact with the airplane dynamics (i.e.: HQDT, refueling, formation flying and landing).

The ultimate goal of the handling qualities design, test and analysis is to optimize the performance of the integrated pilot and airplane system. The testing techniques which typically demonstrate the most representative results consist of aggressive, precision and sustained maneuvers, known as "high gain" pilot tasks. These high gain tasks include precision air-to-air or air-to-ground tracking, close formation flying, aerial refueling and glide slope tracking during landing approaches [23].

In an attempt to quantify the ability of the pilot to accomplish these tasks, two techniques are employed: 1) HQDT plot program [4], and 2) the Cooper-Harper Handling Qualities Rating Scale [2]. The HQDT plotted results are based on analysis of gun camera film of tracking maneuvers flown against specified targets during specified maneuvers. The gun camera film is computer scored and processed to display statistical summaries of pipper (target indicator on heads up display) pitch and azimuth motions relative to the target. In addition to the plotted results for the HQDT maneuvers, the Cooper-Harper rating scale is routinely applied to all high gain tasks. This scale presented in Figure 5, is used during the postflight debriefing to evaluate the pilot's perception of his ability to accomplish the specific task [2]. It is important to note that with the advent of simulators with advanced video displays, these high gain maneuvers can be simulated and analyzed on the ground in the same manner as flight data, with the inherent advantages of the ground based system.

E. Second Generation Data Reduction

As in the performance data reduction, the UFTAS processing is integral to the flying qualities investigation. In the flying qualities situation however, the standard UFTAS function of data smoothing and wild point editing can potentially contaminate the data for certain studies. These include investigations involving the frequency response analysis (FRA) of the dynamic characteristics of the aircraft and its flight control system. Under certain circumstances, attempting to determine the transfer function relationship between various parameters may be complicated by the UFTAS smoothing routines. This smoothing may mask certain high frequency flight control anomalies or augmentation system interactions which cause adverse control problems. Such a situation may be resolved by running the FRA prior to UFTAS processing as identified in Figure 1. Since this type of analysis is not typically required, the detailed FRA capabilities discussion will be reserved for the post-UFTAS discussion.

For the flying qualities case, the UFTAS processing is relatively limited when compared to the performance processing. Included are routines to calculate the following:

1) Position error corrections for the pitot static system,
2) Upwash corrections (wind tunnel derived),
3) Rate corrections,
4) Aircraft gross weight, cg, and moments of inertia, and
5) Wild point editing and data smoothing.

The UFTAS outputs are simply time histories of the corrected values for the parameters in Table 3. The data tape formats of these outputs are configured to be the standard input format for any of the post-UFTAS routines which will be discussed. The UFTAS could be set up to automatically standardize the data, or even run the Modified Maximum

Likelihood Estimator (MMLE) or FRA programs, but since these applications are so maneuver and data quality dependent, further analysis is typically done on a case by case basis.

F. First Generation Data Analysis

As presented in Figure 1, and described in the performance section, the conventional analysis methods consisting of extensive plotting and cross-plotting of data may be utilized for a basic understanding of the flying quality characteristics of the system. References [33] and [30] provide the essential theoretical background material for the classical flying qualities testing and analysis methods. They do not however, describe the advanced tools available for a more complete characterization of the system, and how these tools can be integrated in the analysis process. As presented in Figure 1, a mathematical model capable of simulating the flying qualities characteristics of the aircraft throughout its envelope is the ultimate goal. A high fidelity model of this type allows the analysis team to do the following [30]:

1) Develop and verify flying quality criteria.
2) Extrapolate flight characteristics dependably.
3) Optimize the aircraft's flying quality performance efficiently.
4) Give engineering and operational simulators more accuracy and high fidelity.

5) Reduce flight time required to assess aircraft flight characteristics.

6) Provide a data base for improving analytical and predicted estimates.

During the flight test program, the three primary tools used in the development of, and in conjunction with the flying qualities real time simulator, are the Environmental Control Analysis System (EASY5), the Frequency Response Analysis (FRA), and the Modified Maximum Likelihood Estimator (MMLE) computer programs [12,20,24].

The EASY5 program, as developed by the Boeing Company, is designed to provide a simplified way to describe and analyze linear and nonlinear dynamic systems [20]. The program consists of a Model Generation Program and an Analysis Program. The detailed descriptions of the programs can be found in Reference [20]. Basically, the modeling is accomplished by describing the aircraft flight control system (FCS) in terms of standard components which are subroutines that model specific hardware items, such as rate gyros, or perform certain tasks such as wind gust generation. The EASY5 Model Generation Program generates the required subroutines which represent the model in program form. One capability which is worth mentioning, is that since the model is essentially modular, a new FCS component can be added easily to evaluate its effect on the performance of the system. Once the final configuration is defined, the model is analyzed by any of the linear, nonlinear, steady state or dynamic evaluation techniques available in the EASY5 Analysis Program. Some of the capabilities of the program are as follows [20]:

- Algebraic sensitivity
- Eigenvalue and Eigenvalue sensitivity determination
- Frequency response (Bode, Nyquist and Nicholes plots)
- Linear model generation
- Nonlinear simulation (Time histories)
- Root locus plot generation
- Stability margin determination
- Data standardization

The disadvantages of this program are that it is relatively complex, requires a large effort to develop, and requires a significant amount of computer resources to execute when compared to the other available analysis tools. As a result, the FRA, MMLE and real time simulator are commonly used, prior to developing the EASY5 simulation.

Since the FRA program relies on the SANDS or UFTAS time history data files as inputs, this program represents a simple and fast method of performing frequency domain analysis of the aircraft system [24]. The FRA directive file provides the instructions as to which specific analysis is performed. These directive files can be user generated or specified from the file library. The following directive files are available in the program library:

- One input, ensemble averaged or unaveraged, Power Spectral Density (PSD) function estimation.

- One, two or three input/one output transfer function analysis.
- Analysis of aircraft response to turbulence.
- Analysis of the aircraft vibration environment.

The specific outputs of these directive files vary slightly, but essentially they consist of the following:

- The estimated PSD of the input and output signals.
- Transfer functions between input(s) and output parameters in terms of Bode amplitude and phase angle plots.
- The ordinary (or multiple and partial) coherence function between the input(s) and output signals.
- The 95% confidence limits are computed and plotted for each function.

Reference [24] provides additional information on potential error sources (i.e., data aliasing, time phasing and noise) and methods to improve the input data quality (i.e., parameter selection, averaging and data point optimization). Since FRA is primarily used to identify transfer function relationships between parameters such as stick force and tail position, or yaw rate and rudder position, FRA can be used in conjunction with MMLE in determining the FCS and individual surface effectiveness.

The MMLE is the primary method of developing or updating the stability, control and damping derivative information required for the flying qualities simulation. This program is a maximum likelihood estimator, which uses a modified Newton-Raphson algorithm for convergence [12]. It assumes a linear, time invariant, three-degree-of-freedom model, and that the cases are either longitudinal or lateral-directional. The MMLE derivative extraction is the result of the programs analysis of time history data from specific pilot maneuvers (i.e., pitch or yaw/roll doublets). Once selected, the "best" aerodynamic math model can then be combined with the FCS math model to develop the flying qualities simulation. As previously presented, these aerodynamic derivatives are used to compute frequency, damping, static margin and other Mil Spec parameters.

The six primary reasons to perform derivative analysis rather than relying on the classical analysis techniques are [12]:

1) The added insight provided by derivatives to evaluate individual aspects of the aircraft control and response characteristics.
2) The ability to extrapolate data over angle of attack and Mach number ranges more confidently than frequency and damping extrapolations alone.
3) The ability to standardize more efficiently using derivative relationships.
4) The set of flight derived derivatives allows FCS gain schedules in the simulation to be adjusted and verified prior to confirming in flight.
5) The ability to easily update the simulator with flight derived data.

6) Overall more efficient use of flight test time since required maneuvers are short duration doublet maneuvers and Mil Spec requirements are accomplished as well.

Another advantage which plays an integral role in the integrated flight and ground test effort, is that derivative identification allows for feedback on specific areas of agreement or disagreement between the two data sources.

Reference [12] provides detailed information on specific pilot maneuvers required for optimum data analysis, preparing the time history data for program execution, program equations, and the program assumptions. This reference also provides important derivative accuracy information, assuming the suggested procedures are followed. The expected derivative accuracies are presented in Table 4. The accuracy estimates will provide important data quality guidelines when direct comparisons between the flight and ground test derived data are performed in Chapter IV.

As presented in Figure 1, the refinement of an accurate, high fidelity flying qualities simulation should rely heavily on the EASY5, FRA and MMLE computer programs. While the predicted data base is essential to establish the baseline model, the ease with which it can be updated is critical. Since the FRA and MMLE programs are simple to execute and provide a substantial amount of information, they are optimal for the flight test scenario. In addition since they also provide data easily comparable to the ground test results, they serve as powerful problem solving tools.

G. Second Generation Data Analysis

As in the performance analysis scenario, based upon the integrated ground and flight test analysis results, it is now appropriate to recommend any required flight manual revisions and verify Mil Spec compliance. Whether or not an aircraft flying qualities model was developed, at least a cursory assessment is possible. However, as presented in Figure 1, the availability of an accurate model puts the integrated ground and flight test analysis team in a much better position to investigate adverse characteristics, or evaluate alternate designs. It is worth restating for the flying qualities case that the team approach, with the reliance upon system modeling, should be the standard operating philosophy whenever a major weapon system is being developed.

CHAPTER IV

SIMULATION AND FLIGHT TEST DATA CORRELATIONS AND CONCERNS

A. General

A myriad of studies have been conducted to evaluate and assess the correlation between ground test predictions and the flight test results. References [9], [18], [26], and the author's own experience indicate that three conclusions can be drawn from these studies, which relate to the modeling philosophy presented in this report:

1) The data predictions are a significant function of the time and care taken to include all of the details and the higher order effects of the full scale vehicle.
2) The engineering emphasis and techniques used to improve the relative agreement between the data sources must be applied on a case by case basis.
3) The relative importance or concern expressed over the data correlation is a direct function of either the expectations of the analysis team, or what they are going to use the data for.

With these factors in mind, the following discussion will present comparisons of data from the two sources, and how the integrated ground and flight test team approach presented in Figure 1 might lead to a better assessment of these comparisons.

B. Performance

The following observations by Wood in Reference [26] are applicable to the performance data correlation effort:

1) [While] correlations between performance estimates and flight test is reasonably good ... our ability to predict old technology improves with hind sight, [but] our ability to predict new technology does not necessarily improve with time.
2) The ability to determine the accuracy of the predictions is a direct function of the accuracy of the flight test measurements.
3) [Since] drag prediction accuracy is a direct function of thrust accuracy ... and [in flight test] thrust is "calculated" from a computer deck ... flight test drag is dependent on the estimated thrust.
4) Air frames can modeled [relatively] easily, pilots cannot ...
5) An airframe manufacturer's published estimates depend on who he is negotiating with.

While these observations open up a fairly large can of worms, the integrated approach presented in this report may help to contain them.

With respect to the old versus new technology, the integrated team approach can only help to improve the predictions of new technologies by providing a pool of expertise applying what they collectively know to the particular situation. The advances in modeling and test techniques used by the ground testers, including high through-put, more accurate measurement systems, user friendly, easily updatable predictive models and CFD codes all potentially add to more accurate methods for establishing baseline predictions. The key is getting the ground testers talking to the flight testers to understand each others particular problems, and integrate their technologies to solve them.

An example of the significant effect that the ground test predictions have for the flight testers, is in the determination of aircraft drag. Since aircraft drag is such a dominant parameter in all equations presented in Chapter II of this report, and in flight test, drag accuracy is a direct result of an accurate thrust estimation deck, accurate flight test drag determination is a major effort. If the flight test drag does not agree with the prediction (specifically if it is too high), then significant effort may be involved with determining whether the actual aircraft drag is higher than expected, or the actual aircraft thrust is lower than the estimation deck indicates. In practice however, as far as the test pilot and flight test engineers are concerned, the net effect is that the aircraft performance may be lower than expected, and it is their responsibility to accurately document that level for the operational community. The integrated ground and flight test team on the other hand, would be able to apply their expertise and investigate the areas of possible disagreement. Once the most accurate values for thrust and drag are determined, the team is then equipped to provide the operational users with the most accurate handbook data possible.

A comparison of predicted versus flight test takeoff performance will illustrate how well these data compare, as well as how pilot technique (not a major issue in ground testing) can be minimized in the final evaluation. As outlined in the takeoff and landing modeling procedure presented in Chapter II, and detailed in Reference [1], the T/O&L model is generated by using the flight results to select representative values for thrust application rate, rotation speed, rotation rate, etc. Since these parameters are very pilot dependent and have a large effect on the final model performance, comparisons are made between the observed takeoff distances and those calculated by the model at the same conditions. Figure 6 presents such a comparison for a representative twin engine fighter configuration. Once the model is refined to reflect the actual takeoff performance, comparisons between the flight test based model and the predictions (in this case the preliminary flight manual) can be made. Table 5 presents such a comparison for the twin engine fighter case. For this situation the conclusion was drawn that the predicted flight manual needed to be modified to reflect those results presented in the final model.

The data presented in Table 5 also serves to illustrate how important pilot technique is, and how it can be minimized in generating an engineering model. At an estimated rotation speed of 140 KCAS, the aircraft is rolling down the runway at approximately 236 ft/s. If the pilot delays his rotation by one second, he could potentially delay his ultimate lift-off by 236 ft (approximately 14%) since he would not reach his lift-off lift coefficient until further down the runway [26].

This example demonstrates why modeling the takeoff situation, and establishing nominal values for parameters such as rotation speed and rotation rate helps to normalize similar types of data for direct comparison. The point needs to be made however, that since the pilot will not perform the maneuver exactly the same every time, the model serves more as a mission planning tool of what to generally expect, rather than what will actually occur on a specific mission. When developing the in-flight performance simulation, the components of the DPS model (i.e., lift, drag, thrust and fuel flow) are first refined to reflect the most accurate results based on the combination of the flight test and ground test results. The DPS is then used to emulate the flight test cases and generate the parameters presented in the flight manual (i.e., range factor, optimum cruise Mach number, time to accel, etc.).

With respect to evaluating the components of the model, representative lift and drag comparisons are presented in Table 6 and Figures 7a and 7b [13]. Table 6 presents comparisons at specific conditions for a variable wing sweep configuration, while Figures 7a and 7b present comparisons throughout the envelope for a single engine, delta wing fighter configuration. Reference [9] also presents an extensive correlation study of an air breathing missile configuration. The following observations summarize those findings made during the investigations for these various configurations [9,13]:

1) Excellent agreement in lift versus angle of attack characteristics [is] possible.

2) Good agreement in minimum drag below drag divergence Mach number.

3) Poor agreement is typical for minimum drag in the transonic flight regime, probably caused by tunnel wall interference effects, or shock interactions.

4) Overall scatter or bias in comparisons is commonly due to inaccurate thrust estimation decks, or aircraft instrumentation.

5) Environmental conditions such as wind or wind shears can also contribute to data scatter, especially when relying on inertial navigation system (INS) as a primary acceleration data source.

These observations make a strong case for keeping the entire test team informed regarding specific areas of concern for each phase of testing.

With respect to those performance parameters presented in the flight manual, Table 7 presents a comparison of optimum range Mach numbers and corresponding Range Factors for the twin engine fighter configuration. For this case, the differences of less than ±5 percent between the flight test results and the flight manual predictions are considered small. As a result, modifications to the predicted flight manual were not considered necessary.

For the typical configuration, similar comparisons between the flight and ground test based DPS and the predicted flight manual are also conducted for climb, turning and acceleration performance. When these studies were performed for the fighter configuration, agreements of ±5 percent were again observed, and no modifications to the manuals were deemed necessary.

To complete the performance analysis, the takeoff and landing (T/O&L) model based upon the integrated ground and flight test data bases, is used to compare the flight test results to the flight manual predictions. Table 8 presents these comparisons for the twin engine fighter configuration. As presented, several of these comparisons show differences of greater than ±5 percent (specifically 5.3% and 6.4%). However, since the landing maneuver is so dependent on such variable factors as braking performance, environmental conditions or pilot technique, these differences were not considered large enough to require revisions to the flight manual.

In summary, with respect to comparisons between performance flight test results and predictions, it is reasonable to expect agreements on the order of ±5 percent. However, engineering judgement must play a role in evaluating how well the predictions and test results can realistically be expected to agree. Consistently high or low differences between data sources should cast enough doubt that additional emphasis should be placed on those areas of disagreement. Finally, the use of modeling methods to compare the test results to the predictions can be helpful in isolating the specific causes of disagreement. Since the DPS and T/O&L models consist of component parts such as lift, drag, thrust and braking effectiveness terms, these components can be independently evaluated for accuracy, then integrated into the system model.

C. Flying Qualities

As previously discussed, the aircraft flying qualities are defined in terms of both quantitative measures of the stability and control characteristics, as well as qualitative assessment of the aircraft's handling qualities. Therefore, any assessment of the predicted characteristics is not complete without both numerical comparisons to the flight test results, along with the flight crew's appraisal of the system's handling performance. Obviously the man-in-the-loop simulator must play a key role in the latter comparison. Since the equations of motion act as the driving force for the manned simulator, and the stability and control derivatives are the keys to these equations, as well as any further quantitative analysis, comparisons of these parameters are crucial to any correlation study.

Figures 8 through 19 present a set of stability and control derivatives for a single engine, fighter configuration [30]. These derivatives were extracted as functions of angle of attack and Mach number throughout most of the flight test envelope. The maneuvers consisted of a matrix of pitch, rudder and aileron doublets accomplished from 2 to 28 degrees angle of attack, and from 0.30 to 1.65 Mach number. The derivatives were extracted from the flight test doublet maneuvers using the MMLE processing methods described in Reference [32]. The following observations summarize this comparative analysis as well as related studies presented in Reference [30]:

1) Although some derivatives can be determined more accurately than others (see Table 4), the most important derivatives can be determined most accurately.

2) Analytical estimates which neglect aeroelastic effects can be seriously in error. Also, due to the strong aeroelastic effects on the flight test vehicle, the flight test derived derivatives should be presented as functions of dynamic pressure.

3) Monte Carlo simulations conducted on the MMLE process show that the use of accurate constants in the MMLE program, such as aircraft weight, CG and mass moment of inertia is essential.

4) The combination of using the wind tunnel results to anchor the initial estimates in the MMLE process, then using the flight test results to refine the derivatives, is the most accurate method of derivative determination currently available.

5) Knowing the limitations of the MMLE process used during the flight testing, and the potential error sources from both the wind tunnel and flight test data sources, gives the analysis team important information in assessing the quality of the results.

These figures also demonstrate that typically, the agreement between the predictions and the flight test data is within the expected accuracy ranges presented in Table 4. These results are comforting since the required wind tunnel to flight test correction techniques for interpolation, adjustment and extrapolation are typically as much a part of the predictions of the full scale flight data as the predictions themselves. Ultimately, engineering judgement must be applied on a case by case basis to evaluate how important these effects, as well as the following sources of error are, in both the ground and flight test data bases [12,26,33]:

1) The lack of precise aeroelastic modeling capabiliti.e.s in the wind tunnel, and the uncertainty of what the aircraft actually does in flight at different Mach number, dynamic pressure, load factor and angle of attack combinations.
2) Reynolds number effects due to model scaling, and especially at elevated angles of attack due to separation characteristics.
3) Inaccurate corrections of wind tunnel data due to wall and power effects, protuberances, and aeroelasticity.
4) Inability to precisely define aircraft "constants", such as weight, CG and mass moment of inertia due to adding flight test hardware, fuel consumption and fuel distribution during the course of the flight test program or even during a particular flight.
5) Instrumentation health and accuracy of both wind tunnel and flight test measurement systems and analysis methods.

As in the performance situation, there will probably be as many "good" ground test to flight test data correlations as there will be "bad" [26]. However it is reasonable to expect that with the planning and expertise the integrated team can provide, the relative agreement between the two data sources should be no worse than presented in this report. The important point is that the integrated ground and flight test and analysis team, relying on easily refined system models to simulate the actual vehicle, will have a larger, more accurate data base with which to work with. In addition, since the pilot is most familiar with, and must be satisfied with the aircraft's flying qualities, his satisfaction with the manned simulation's fidelity should provide the emphasis for the team to make it accurately simulate the aircraft.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

A technical method of integrating ground test data into the flight test investigations for the evaluation of aircraft performance and flying qualities was presented. This method relies on the extensive use of software models to simulate the aircraft's capabilities. The modeling methods which were described are currently in use for the flight test evaluation, however, descriptions were provided to demonstrate how the ground test data results can be readily integrated into them. Overall requirements for the flight test program are also provided to demonstrate how effective use of modeling techniques can be directly applied to the operational scenario.

The integrated approach which was presented, is applicable to any aircraft system which requires ground testing for prediction generation, and flight testing for prediction verification. For the developmental test efforts of the United States Air Force (USAF) the separate responsibilities of the System Program Offices (SPOs), Arnold Engineering Development Center (AEDC), and the Air Force Flight Test Center (AFFTC), serve to hinder the required information exchange of the integrated test approach. Since all of these organizations are involved with evaluating the same system, a means of continuous and accurate information exchange directly between the USAF ground test and flight test organizations at AEDC and the AFFTC should be established to facilitate the overall Development, Test and Evaluation effort of the SPOs. Although a technical method of this integrated approach for only the performance and flying qualities disciplines was outlined in this report, any of the other areas of technical interest identified in Table 1 should benefit from an integrated team effort. In fact, the recent establishment of the USAF Seek Eagle Program Office at Eglin Air Force Base, Florida, responsible for integrating the ground and flight test efforts related to aircraft store compatibility issues, demonstrates the importance of an agency to coordinate efforts of the various test organizations.

Descriptions of the basic parameters required for the performance and flying qualities studies were provided. It was also described how these parameters are ultimately used in the presentation of flight manual data or performance and flying qualities model simulations. Since the same basic parameters arise from either the ground or flight test data analysis, it was emphasized that the modeling techniques discussed could be taken advantage of using either data source. In fact, for data comparison purposes, flight manual generation and model flexibility, it is recommended that the development of system models first based on ground test predictions then updated by actual flight test data, should be the standard procedure for the evaluation of any system.

The combination of continuous information exchange between testing organizations, and the reliance on system models to simulate the vehicles operating characteristics, have potentially important applications for the various situations encountered in the development process. Problem areas identified in the simulator can be investigated prior to flight and approached cautiously during test missions. Specific problems discovered during flight test can be thoroughly diagnosed and proposed fixes evaluated in the simulator. In addition, serious problems requiring new baseline configurations and data bases can be ground tested, and these results quickly integrated into the system model for flight test verification. In summary, the team approach to ground and flight test evaluations, along with the reliance on constantly updatable simulations, provides program managers and engineers with the most accurate information with regards to their systems capabilities. This team approach, with reliance upon system modeling, should be the standard operating philosophy whenever a weapon system is being developed.

The following related areas of concern, although not included in this study, should be considered for future investigation:

1) Thorough error analysis of the individual modeling techniques discussed, along with the combined effects on the final model.
2) Descriptions of the specific methods used to obtain the ground test results.
3) The application of new or existing technologies to the integrated testing approach, such as laser data acquisition systems, computational fluid dynamics methods and miniaturized data acquisition systems.

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APPENDICES

APPENDIX A

FIGURES

This appendix presents Figures 1 through 19 cited in the main text.

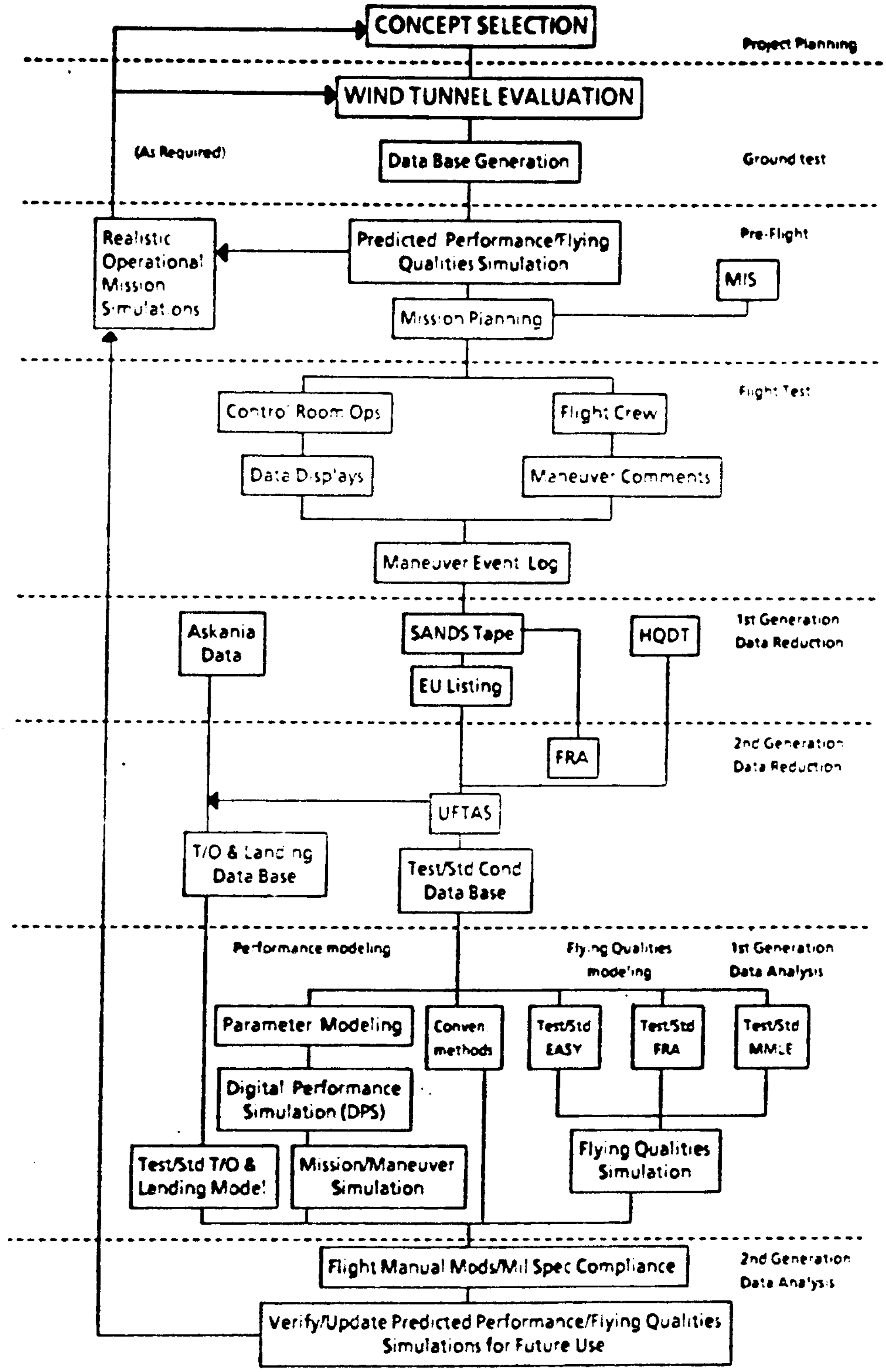


Figure 1. Proposed Integrated Testing and Analysis Flowchart

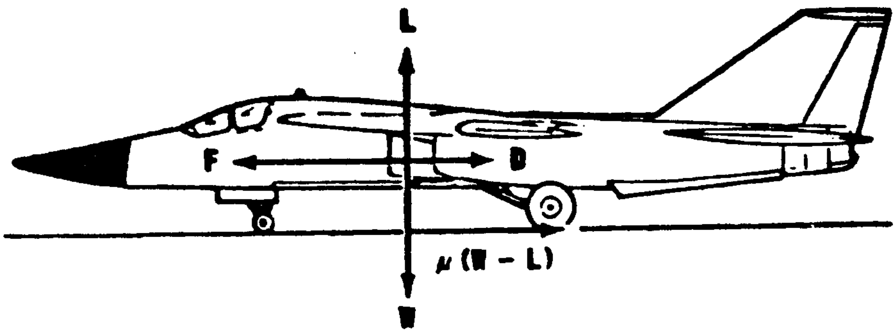


Figure 2. Forces Acting on Aircraft During Takeoff Ground Roll [31]

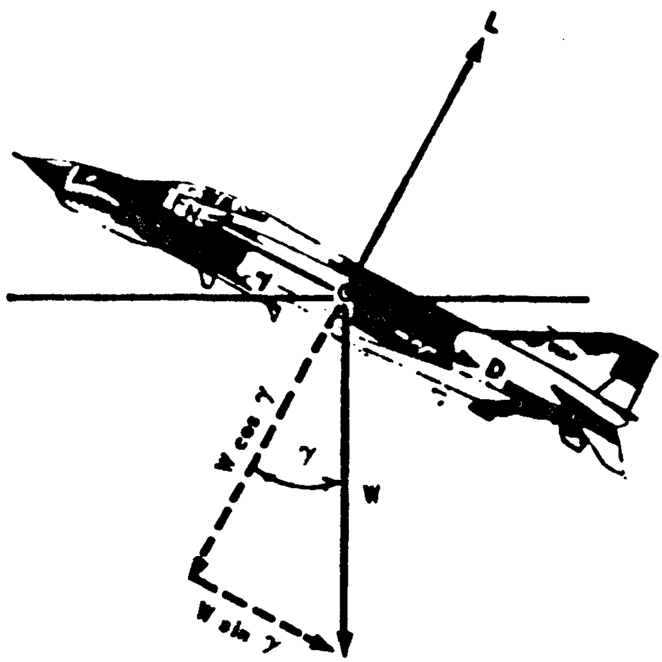


Figure 3. Forces Acting on Aircraft During Climb [31]

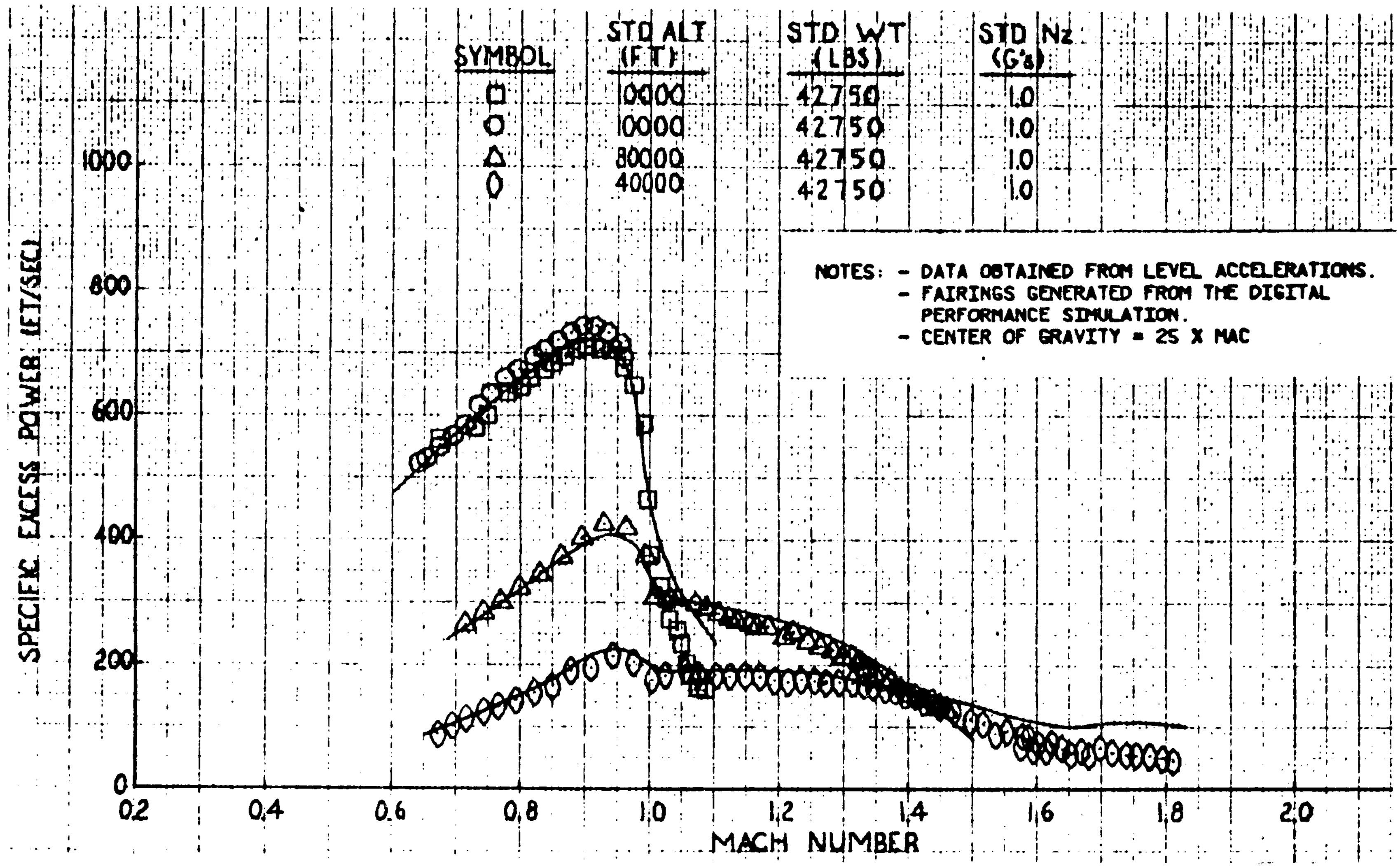


Figure 4. Level Acceleration Specific Excess Power Plot for Twin Engine Fighter Configuration

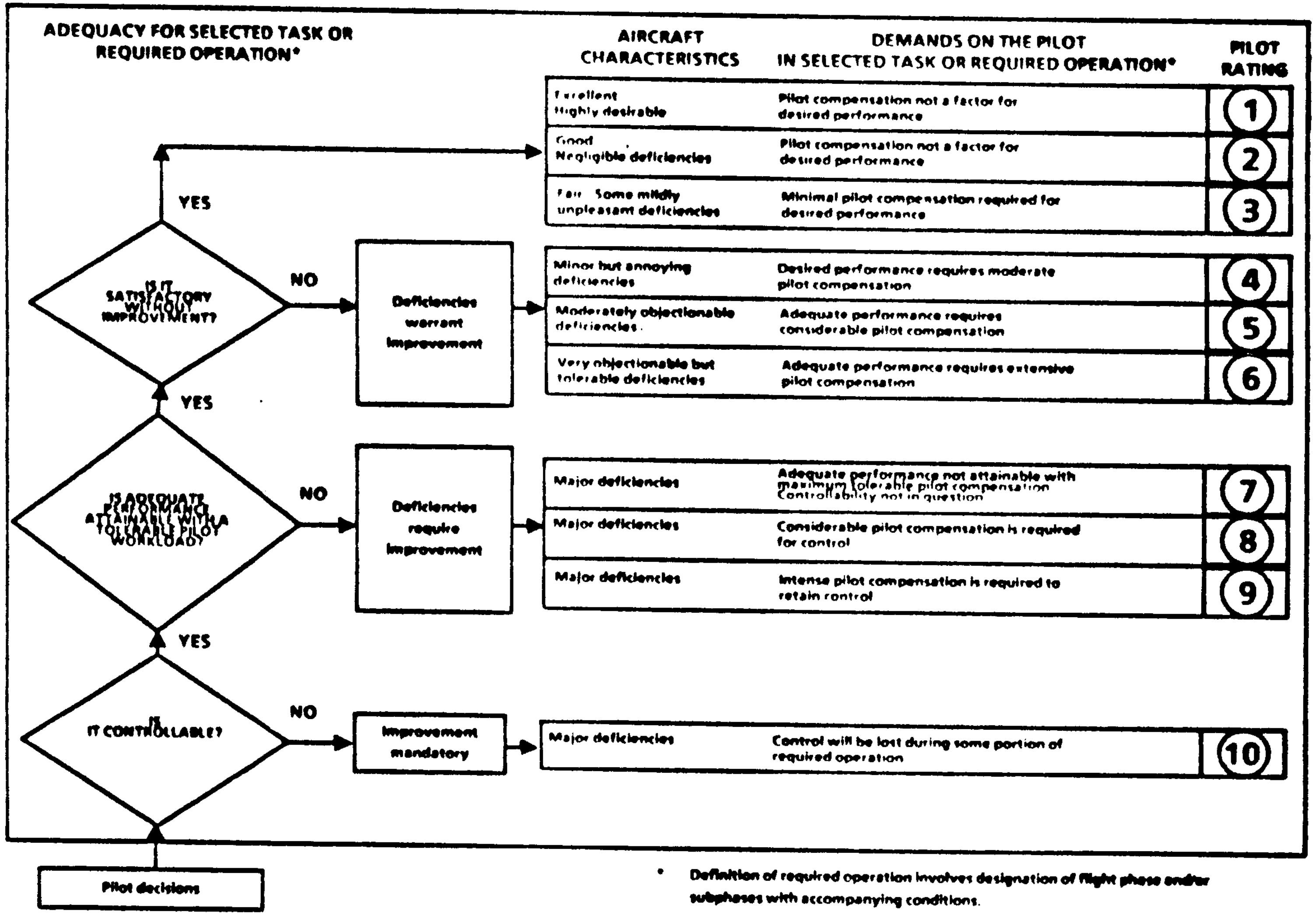


Figure 5. Handling Qualities Rating Scale (Cooper-Harper Scale) [2]

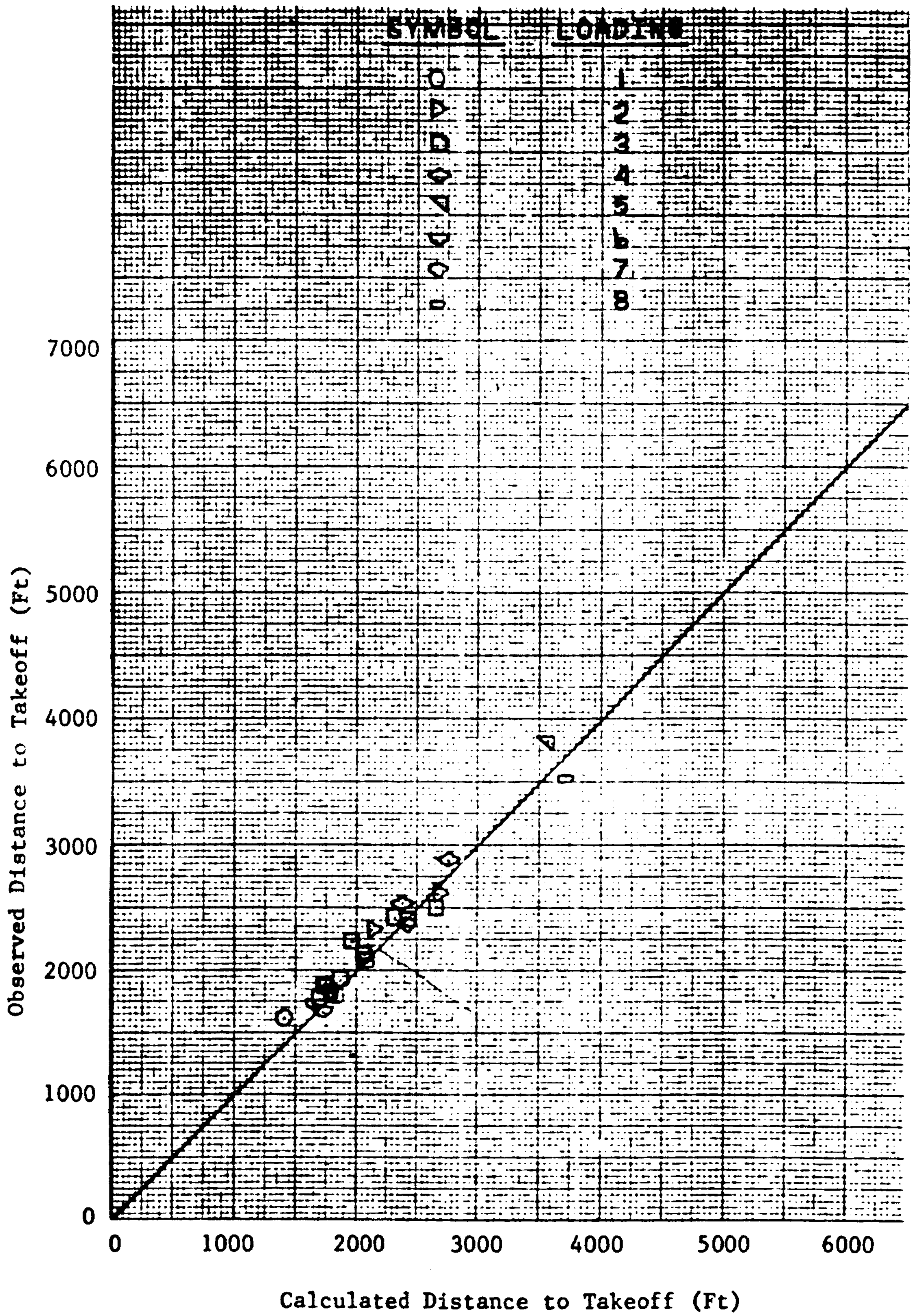
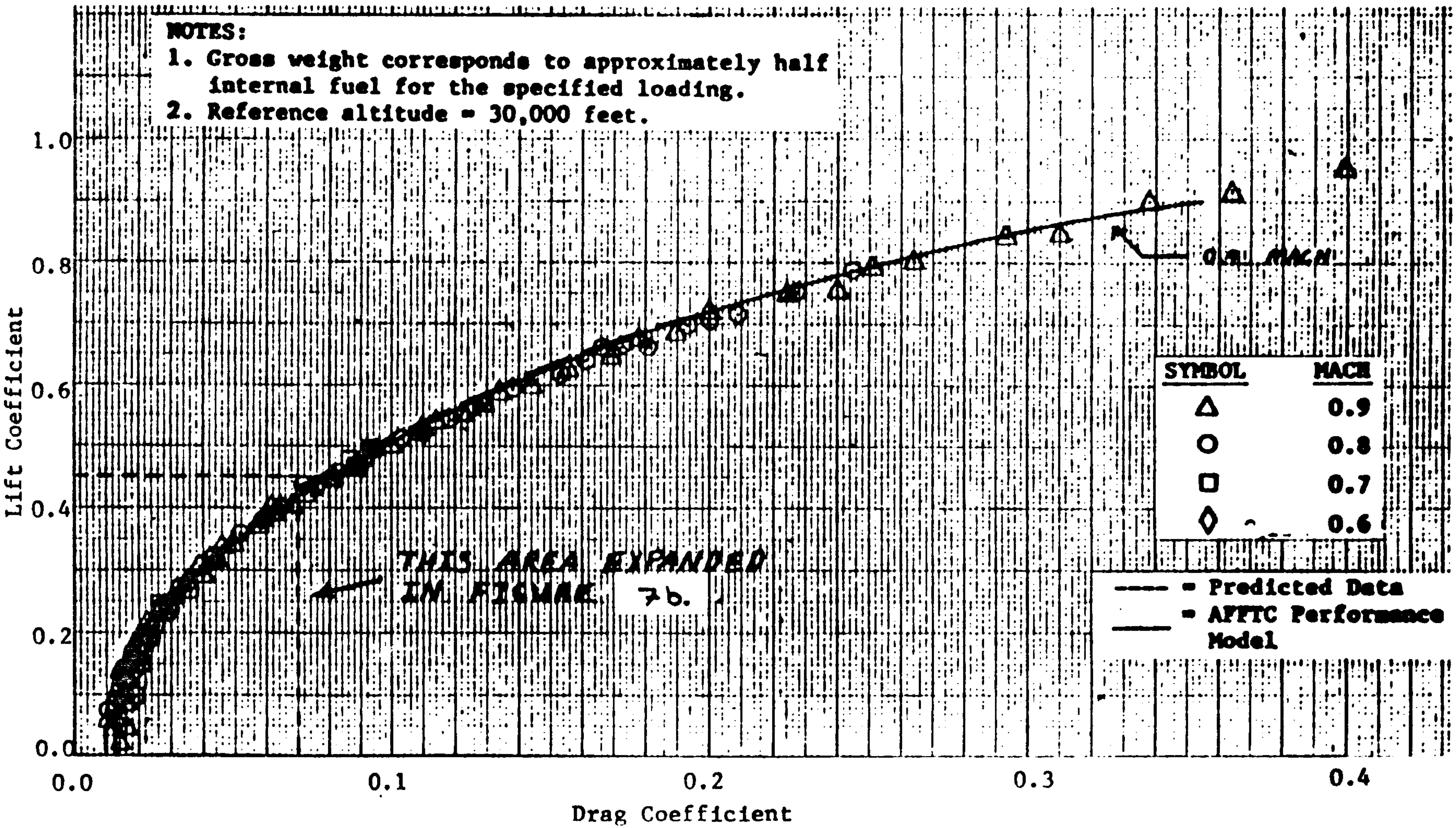
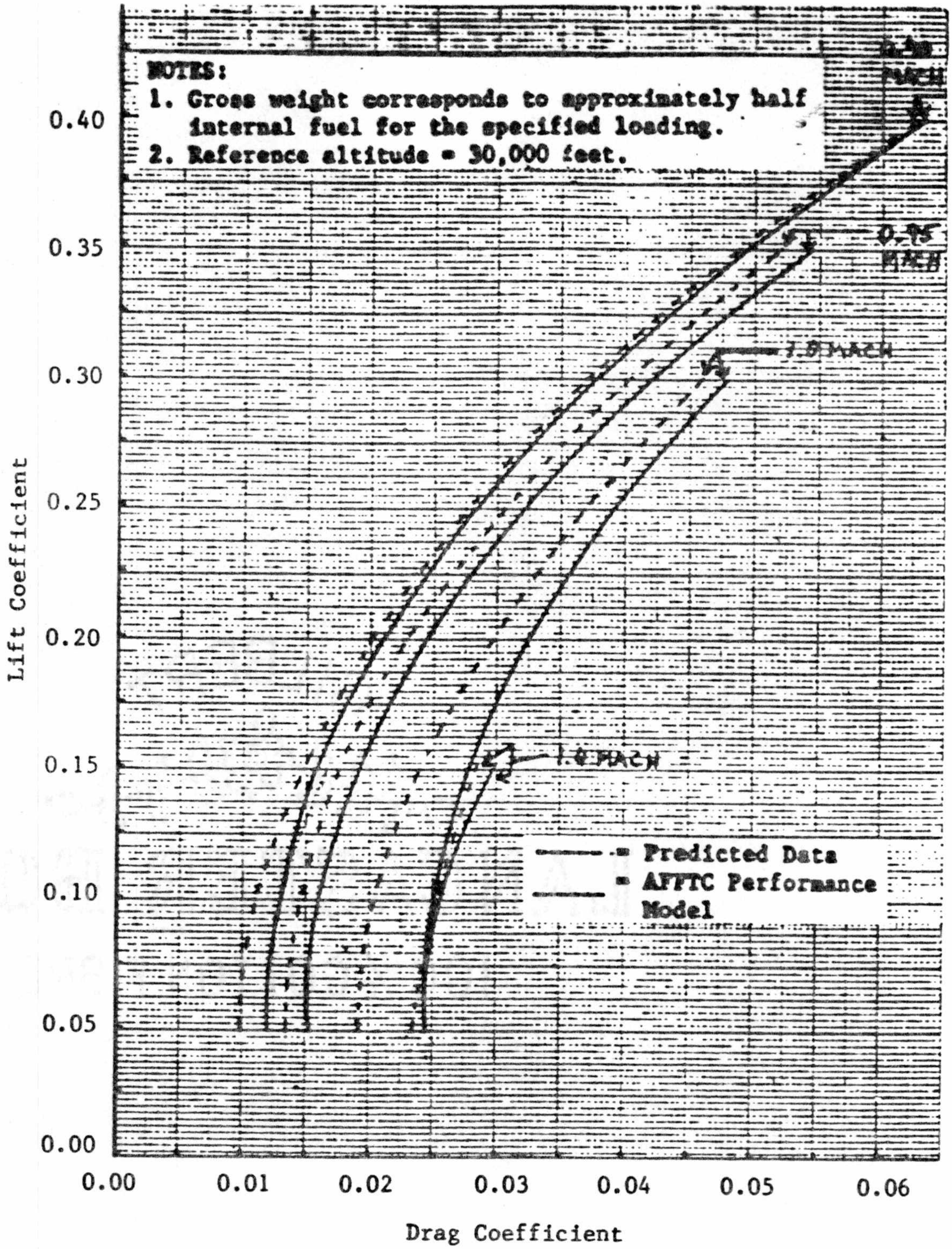


Figure 6. Observed versus Calculated Takeoff Distances for Twin Engine Fighter Configuration



a. Complete Drag Polar for Cruise Configuration

Figure 7. Flight Test versus Predicted Drag Polar Comparison for Single Engine Fighter Configuration [3]



b. Minimum Drag Comparison for Cruise Configuration

Figure 7. Concluded

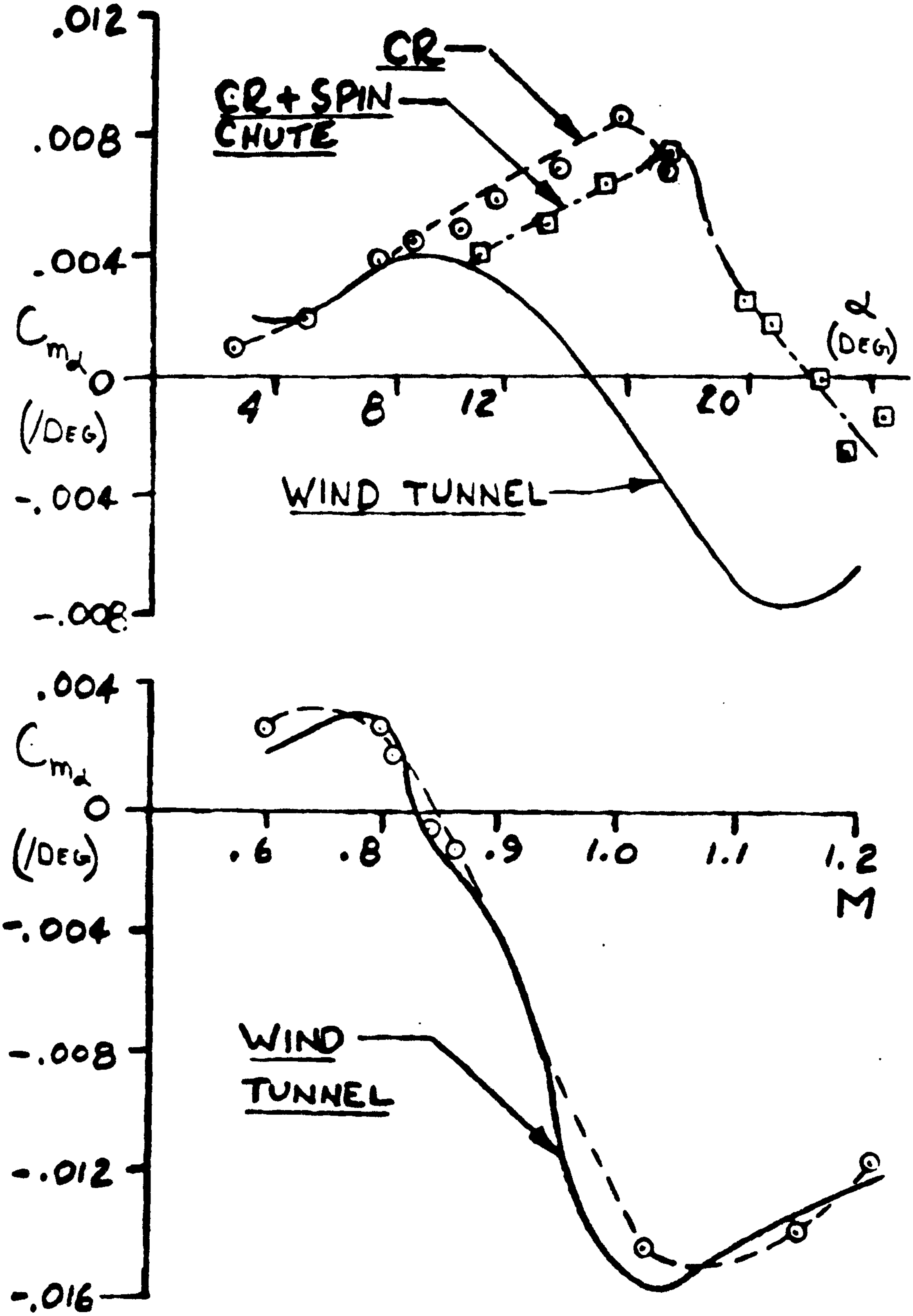


Figure 8. Flight Test versus Predicted C_{m_α} Comparison for Single Engine Fighter Configuration [4]

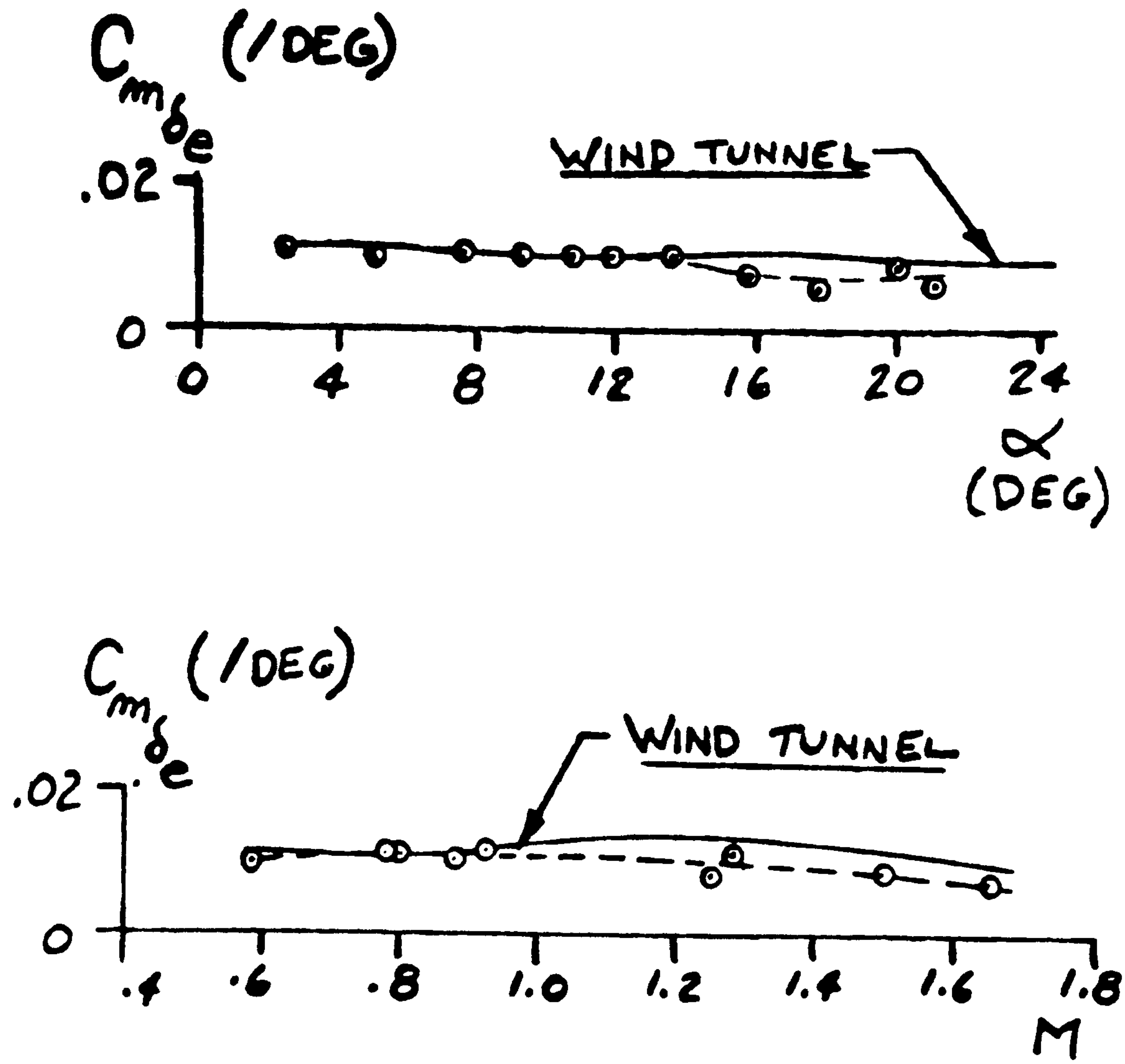


Figure 9. Flight Test versus Predicted $C_{m_{\delta_e}}$ Comparison for Single Engine Fighter Configuration [30]

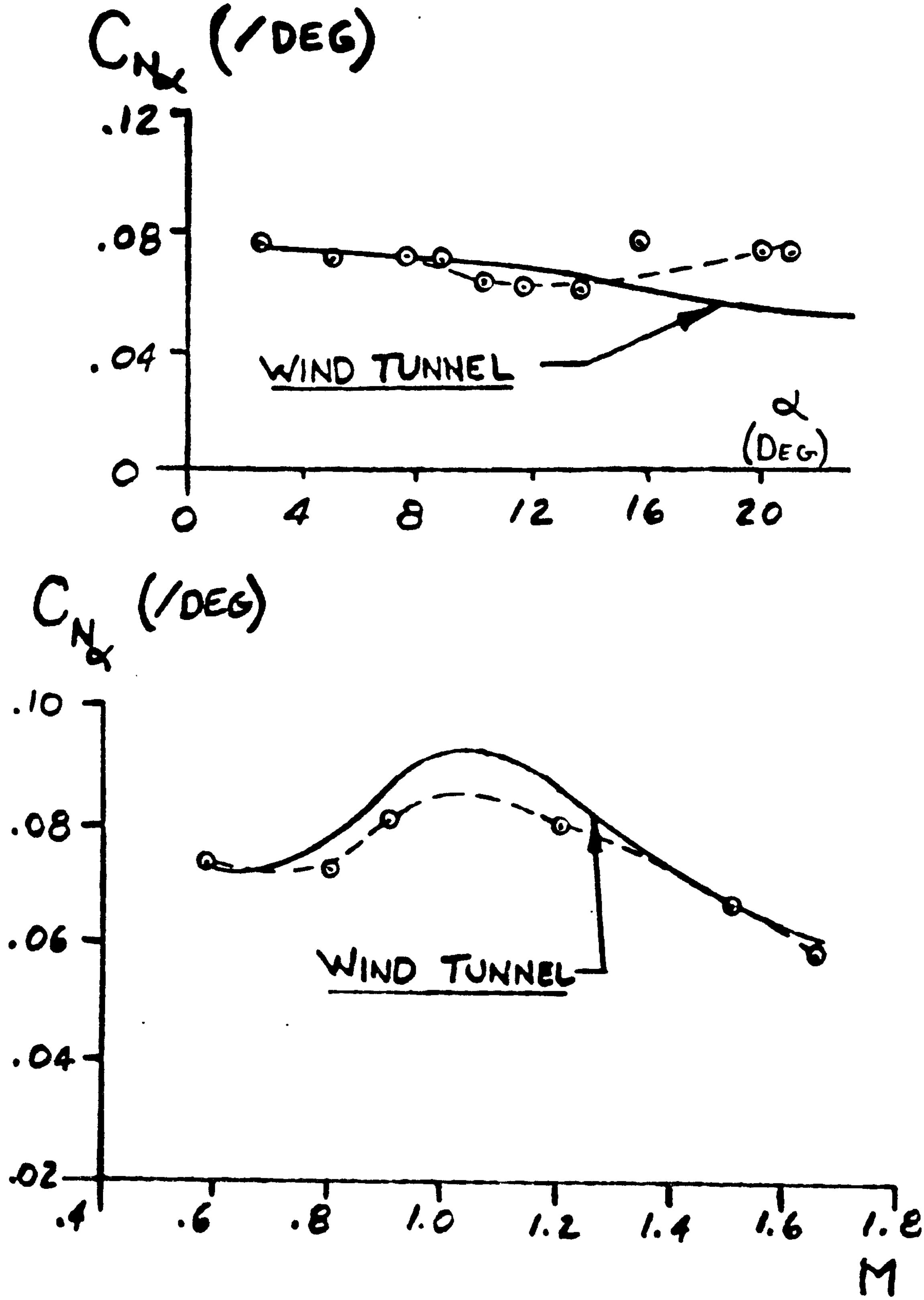
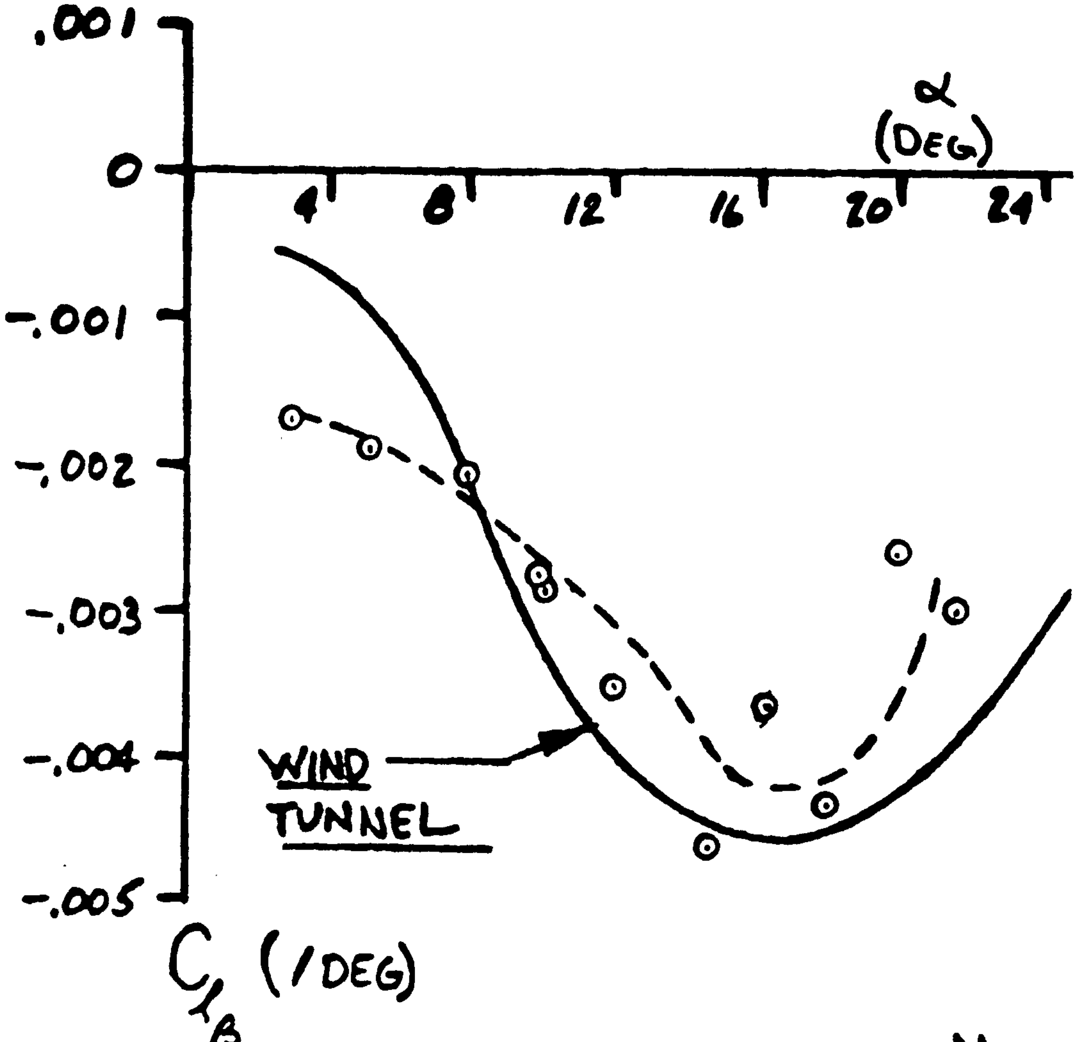


Figure 10. Flight Test versus Predicted C_{N_α} Comparison for Single Engine Fighter Configuration [30]



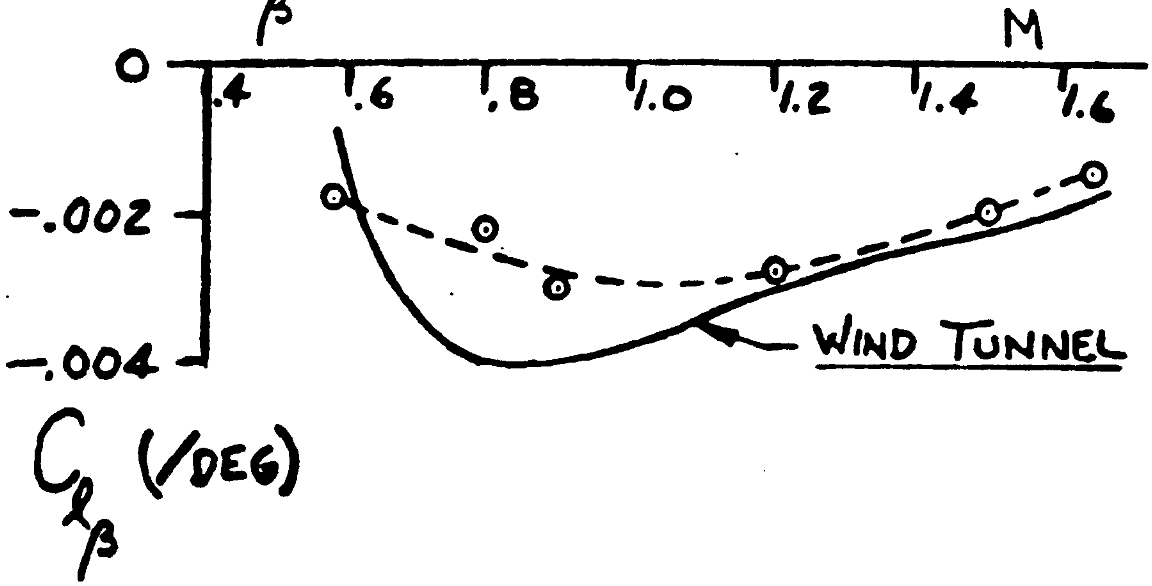


Figure 11. Flight Test versus Predicted C_{ℓ_β} Comparison for Single Engine Fighter Configuration [30]

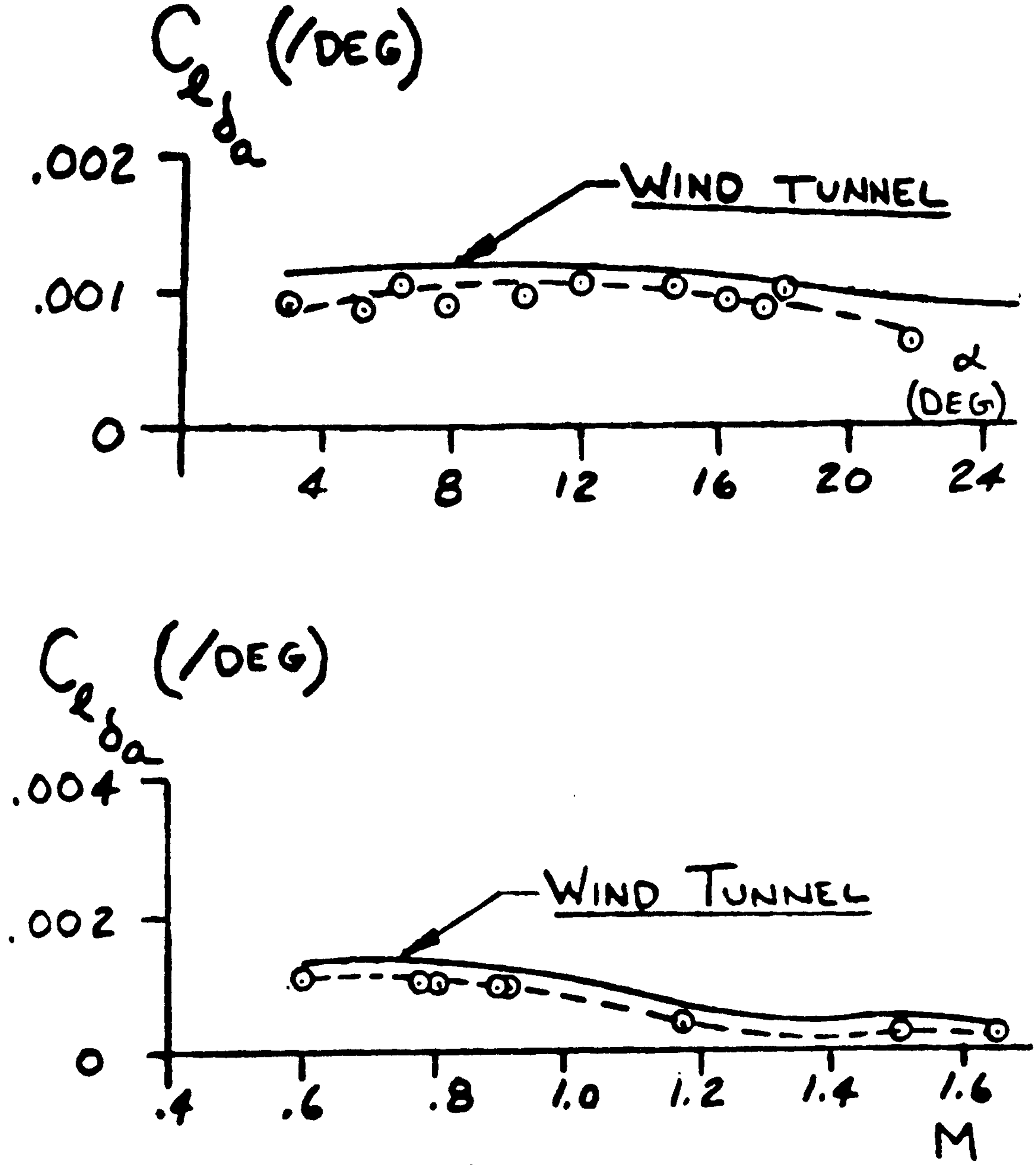


Figure 12. Flight Test versus Predicted $C_{\ell_{\delta a}}$ Comparison for Single Engine Fighter Configuration [30]

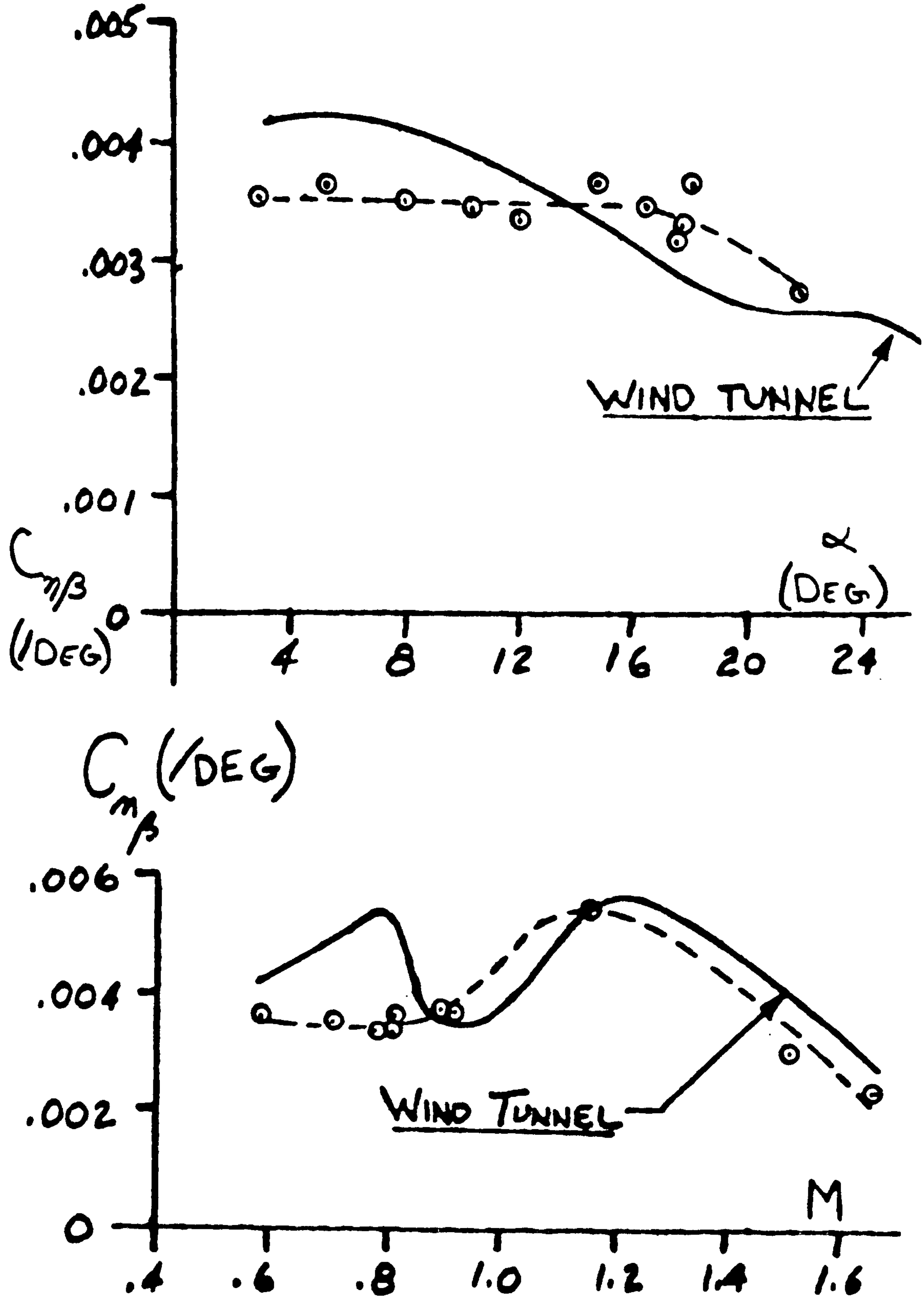


Figure 13. Flight Test versus Predicted C_{n_β} Comparison for Single Engine Fighter Configuration [30]

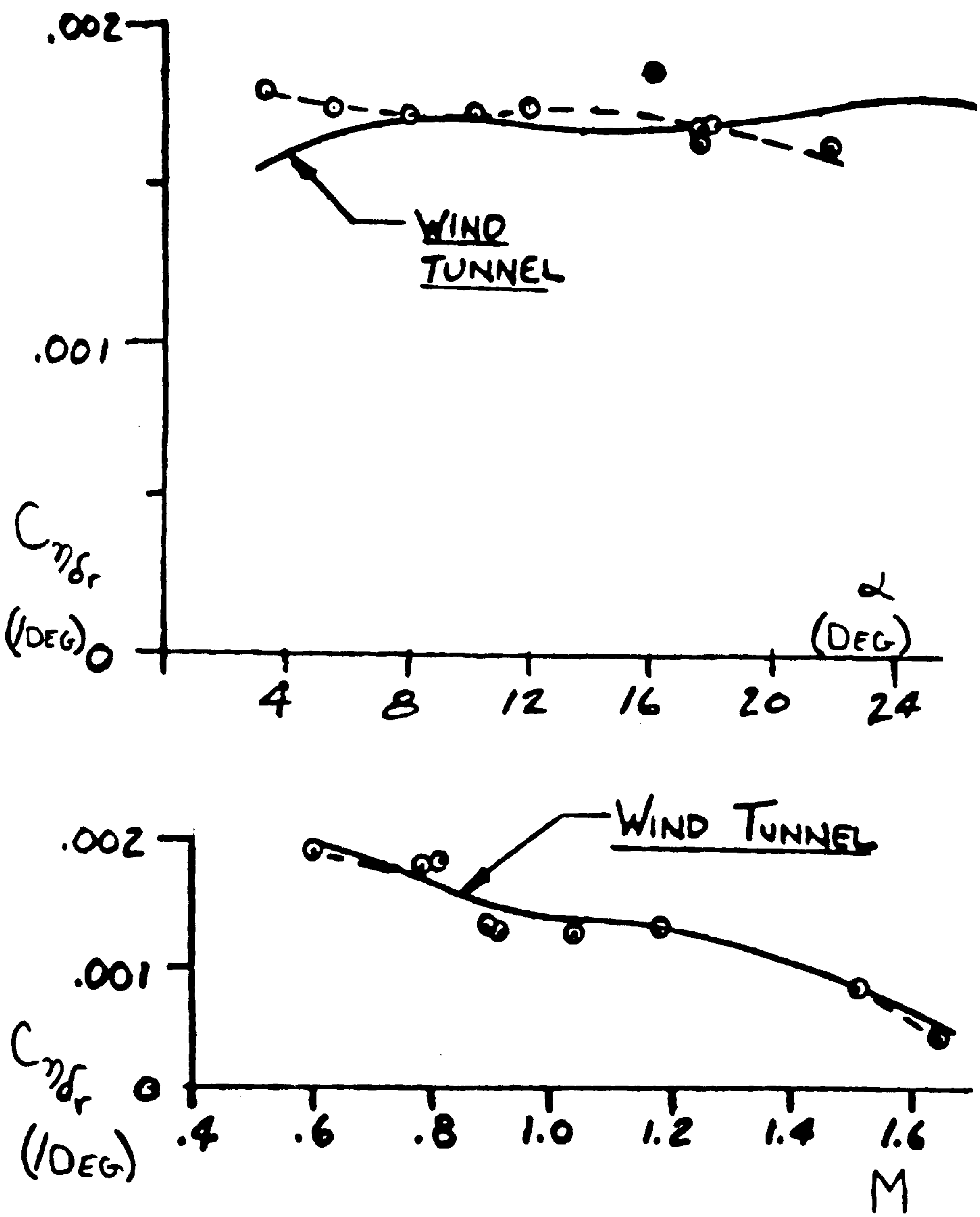
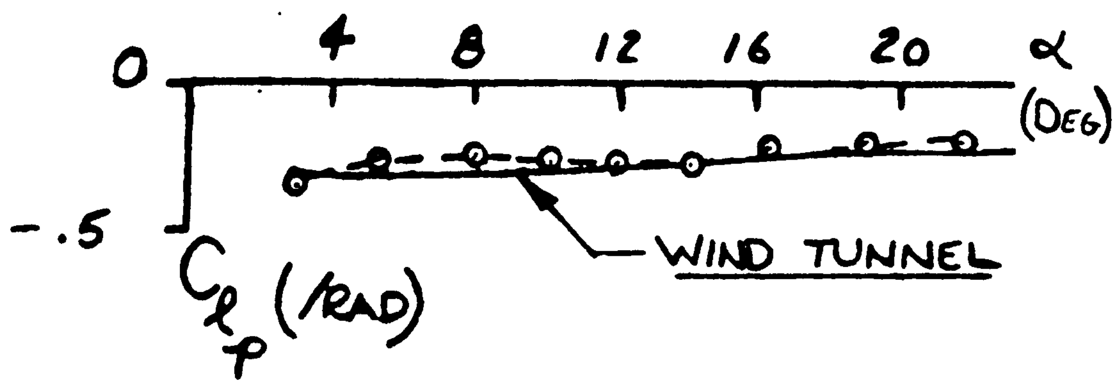


Figure 14. Flight Test versus Predicted $C_{n_{\delta r}}$ Comparison for Single Engine Fighter Configuration [30]



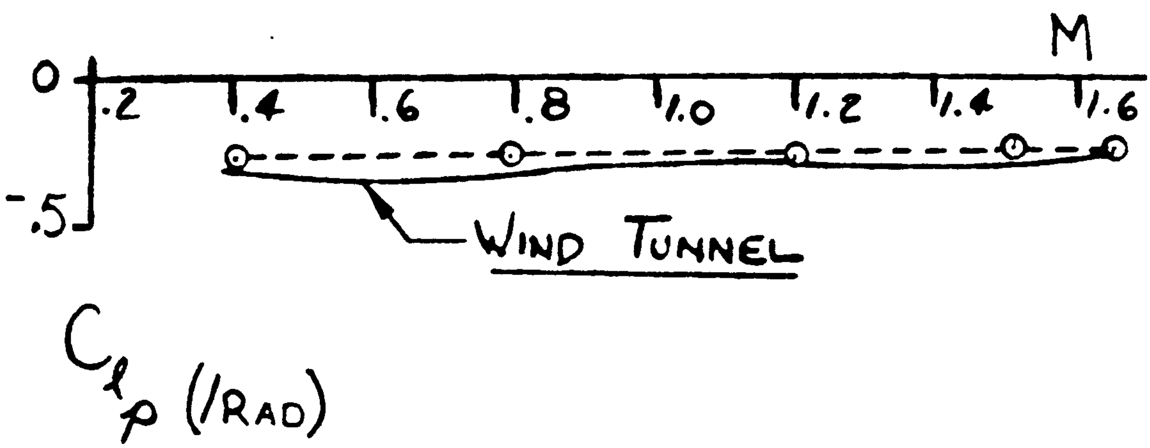


Figure 15. Flight Test versus Predicted C_{ℓ_p} Comparison for Single Engine Fighter Configuration [30]

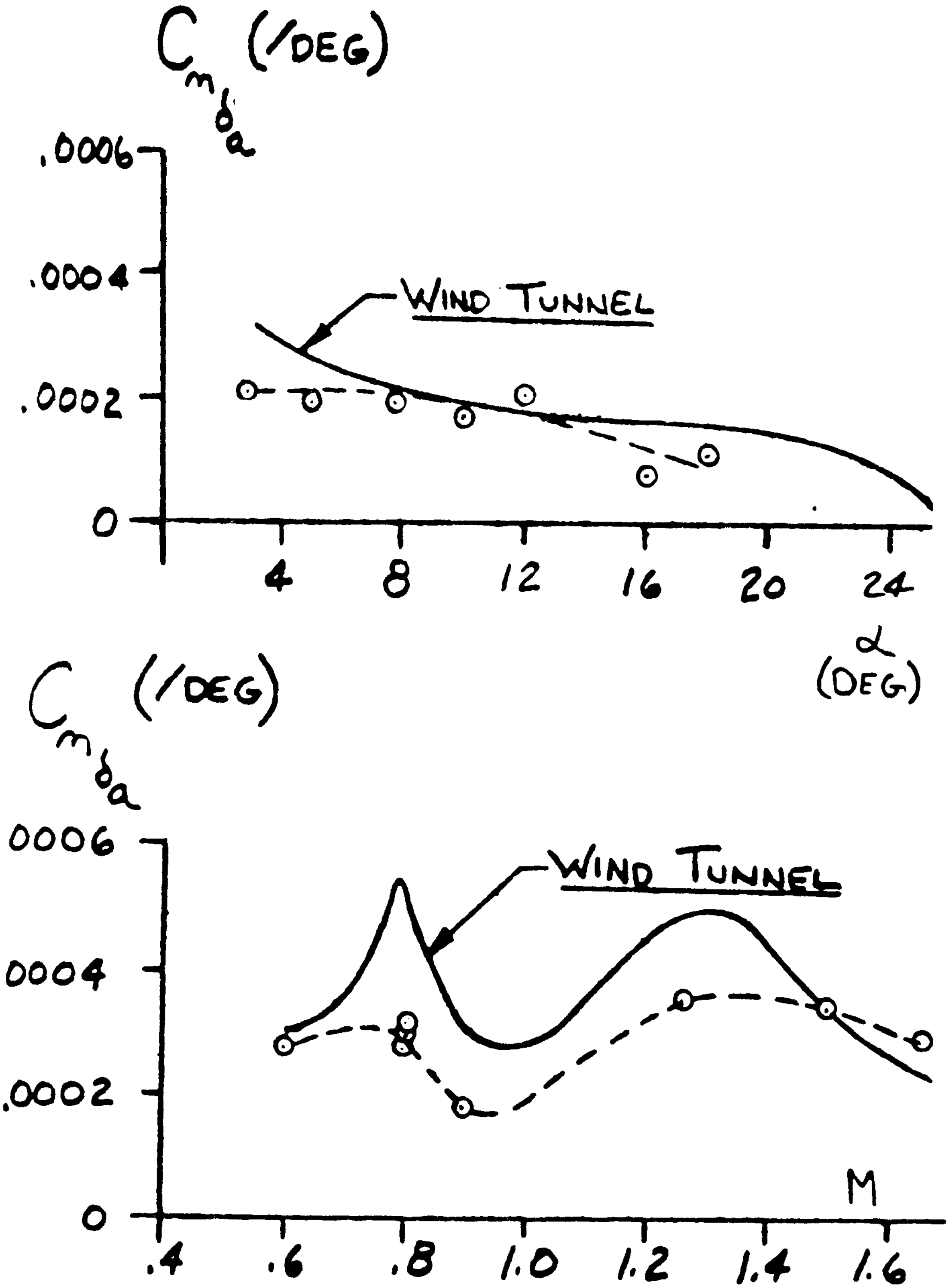
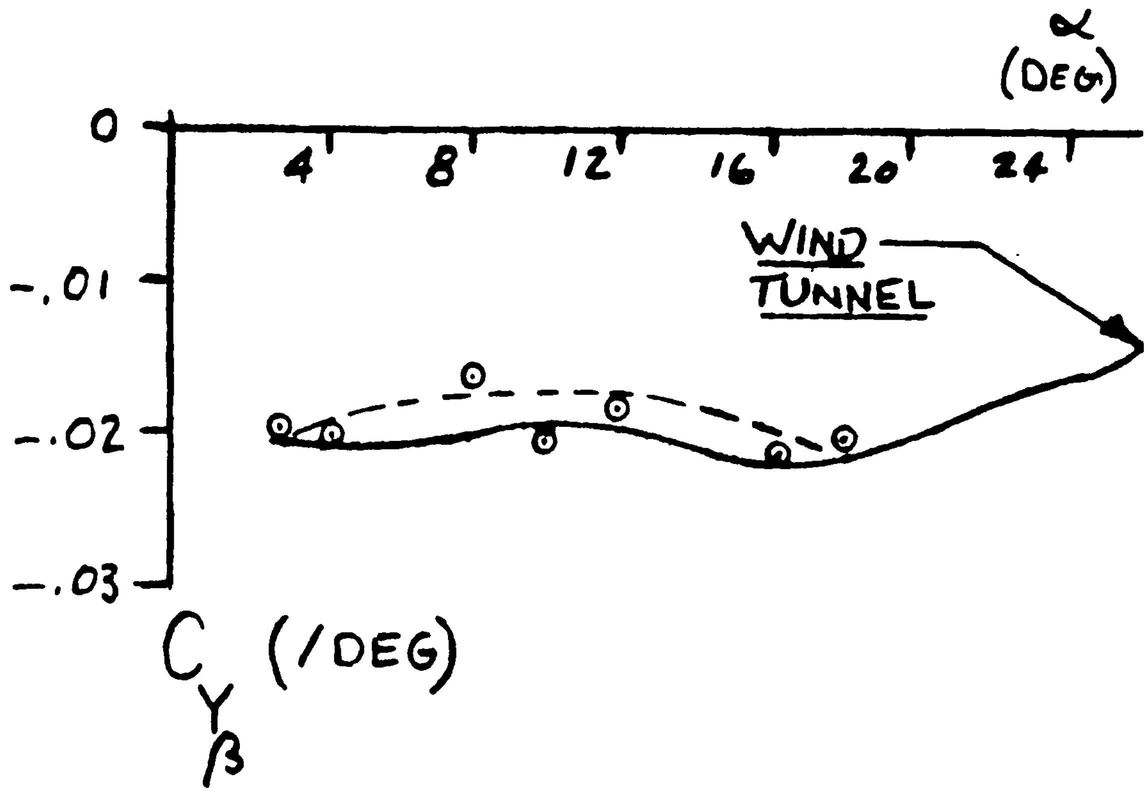


Figure 16. Flight Test versus Predicted $C_{n_{\delta a}}$ Comparison for Single Engine Fighter Configuration [30]



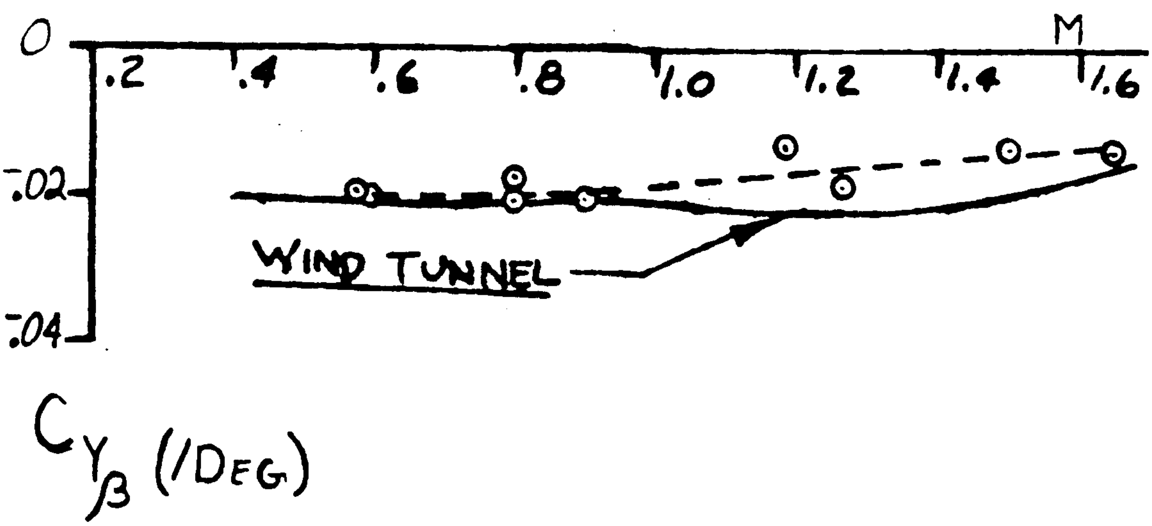


Figure 17. Flight Test versus Predicted C_{y_β} Comparison for Single Engine Fighter Configuration [30]

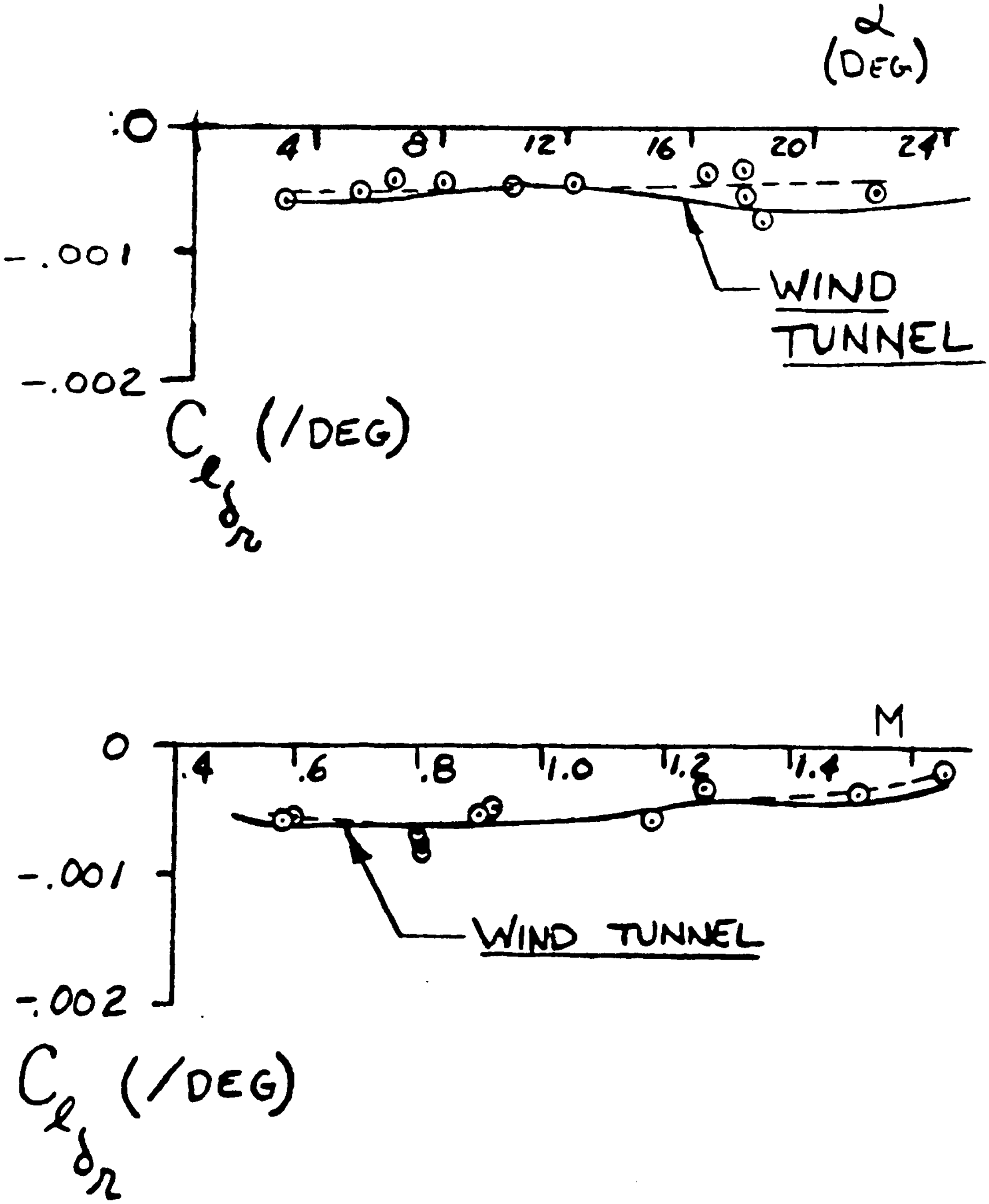


Figure 18. Flight Test versus Predicted $C_{\ell_{\delta r}}$ Comparison for Single Engine Fighter Configuration [30]

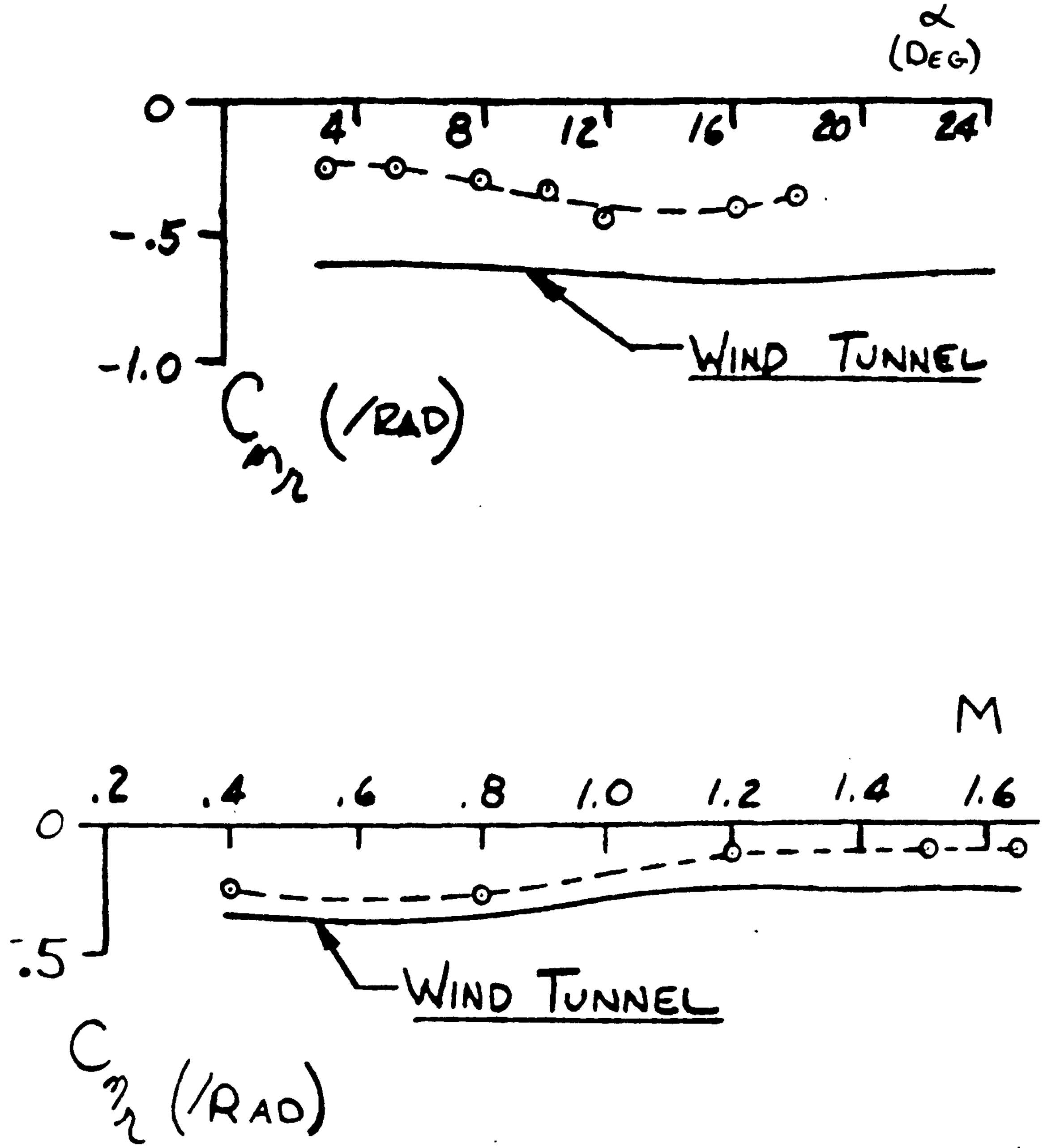


Figure 19. Flight Test versus Predicted C_{n_r} Comparison for Single Engine Fighter Configuration [30]

APPENDIX B

TABLES

This appendix presents Tables 1 through 8 cited in the main text.

	AERIAL REFUELING	AIRCRAFT PERFORMANCE	AIRFRAME SYSTEMS	ALL-WEATHER	ARMAMENT SYSTEMS	AVIONICS SYSTEMS	DECELERATING DEVICES	FLYING QUAL/FLT CONT	HUMAN FACTORS	OPERATIONAL TRAINERS	PROPULSION SYSTEMS	RELIABILITY & MAINTAINABILITY	STORE SEPARATION	STRUCTURAL DYNAMICS	SURVIVABILITY
AERIAL REFUELING			X	X		X		X	X						
AIRCRAFT PERFORMANCE					X			X			X		X		
AIRFRAME SYSTEMS	X			X	X	X	X	X	X	X	X	X			X
ALL-WEATHER			X		X	X		X	X		X	X			
ARMAMENT SYSTEMS		X	X	X		X	X	X	X	X	X	X	X	X	
AVIONICS SYSTEMS	X		X	X	X			X	X	X		X	X		X
DECELERATING DEVICES			X		X			X	X					X	
FLYING QUAL/FLT CONT	X	X	X	X	X	X	X		X	X	X	X	X	X	
HUMAN FACTORS	X		X	X	X	X	X	X		X	X	X			
OPERATIONAL TRAINERS			X		X	X		X	X		X	X			
PROPULSION SYSTEMS		X	X	X	X			X	X	X		X			X
RELIABILITY & MAINT			X	X	X	X		X	X	X	X				
STORE SEPARATION		X			X	X		X						X	
STRUCTURAL DYNAMICS					X		X	X					X		
SURVIVABILITY			X			X			X	X	X				

Table 1. Potential DT & E Test Area Interfaces

Table 2. Typical On-Board Performance Instrumentation Parameters

Parameter	Range	Resolution	Units	Sample Rate (Samples/Sec)
Noseboom (N/B) Airspeed	0 to 850	0.06	kts	10
N/B Altitude	0 to 80,000	1.3	ft	10
Longitudinal cg Accel.	-2 to 4	0.006	g's	20
Lateral cg Acceleration	±2	0.004	g's	20
Normal cg Acceleration	-4 to 12	0.015	g's	20
ADC Total Temperature	-15 to 250	0.1	deg C	10
N/B Sideslip Angle	±25	0.003	deg	40
N/B Angle of Attack	-10 to 40	0.005	deg	40
FPA Total Temperature	-50 to 250	0.1	deg C	10
FPA Nx at N/B	±2	0.001	g's	10
FPA Nz at N/B	-3 to 8	0.003	g's	10
FPA Assembly Temp	-50 to 250	0.1	deg C	10
Lateral Stick Position	±4.5	0.01	in	40
Longitudinal Stick Pos.	-3 to 6	0.01	in	40
L/H Stabilator Position	-30 to 15	0.05	deg	10
R/H Stabilator Position	-30 to 15	0.05	deg	10
Pitch Rate	±30	0.07	deg/sec	10
Roll Rate	±250	0.8	deg/sec	10
Yaw Rate	±30	0.08	deg/sec	10
ADC True Airspeed	0 to 2500	0.1	kts	10
ADC Pressure Altitude	0 to 80,000	1.3	ft	10
ADC Calibrated Airspeed	0 to 1000	0.06	kts	10
Mach Number	0.1 to 3	0.0002	--	10
ADC Angle of Attack	-10 to 40	0.01	deg	10
INS Pitch Angle	±180	0.02	deg	10
INS Roll Angle	±180	0.02	deg	10
INS E/W Velocity	±4000	0.1	ft/sec	10
INS N/S Velocity	±4000	0.1	ft/sec	10
INS True Heading	±180	0.02	deg	10
INS Altitude	0 to 80,000	1.3	ft	10
INS Rate of Climb	±2000	0.13	ft/sec	10
INS E/W Acceleration	±250	0.25	ft/sec2	10
INS N/S Acceleration	±250	0.25	ft/sec2	10
INS Vertical Accel.	±500	0.25	ft/sec2	10
Data Run Number	0 to 1000	--	--	10
Pilot Voice	--	--	--	20,000
L/H PLA	0 to 130	0.05	deg	10
R/H PLA	0 to 130	0.05	deg	10

Table 2. Continued

Parameter	Range	Resolution	Units	Sample Rate (Samples/Sec)
L/H Cowl Angle	1 to 10	0.01	in	10
R/H Cowl Angle	1 to 10	0.01	in	10
L/H Nozzle Area (AJ)	2.5 to 6	0.01	ft^2	10
R/H Nozzle Area (AJ)	2.5 to 6	0.01	ft^2	10
L/H Fan Speed (N1)	5 to 120	0.15	pct	10
R/H Fan Speed (N1)	5 to 120	0.15	pct	10
L/H Comp. Speed (N2)	5 to 120	0.15	pct	10
R/H Comp. Speed (N2)	5 to 120	0.15	pct	10
L/H Fuel Flow	0 to 100,000	105.5	lb/hr	10
R/H Fuel Flow	0 to 100,000	105.5	lb/hr	10
Total Fuel Quantity	0 to 25,000	25.0	lb	10
L/H Fuel Temperature	0 to 300	0.1	deg F	10
R/H Fuel Temperature	0 to 300	0.1	deg F	10
L/H FTIT	0 to 1200	1.0	deg C	10
R/H FTIT	0 to 1200	1.0	deg C	10
L/H Burner Pressure (Pb)	0 to 50	0.03	psia	10
R/H Burner Pressure (Pb)	0 to 50	0.03	psia	10
L/H Pt6	0 to 50	0.03	psia	10
R/H Pt6	0 to 50	0.03	psia	10
L/H Tt2	0 to 500	0.5	deg F	10
R/H Tt2	0 to 500	0.5	deg F	10

Table 3. Typical On-Board Flying Qualities Instrumentation Parameters

Parameter	Range	Resolution	Units	Sample Rate (Samples/Sec)
Noseboom (N/B) Airspeed	0 to 850	0.06	kts	10
N/B Altitude	0 to 80,000	1.3	ft	10
Longitudinal cg Accel.	-2 to 4	0.006	g's	20
Lateral cg Acceleration	±2	0.004	g's	20
Normal cg Acceleration	-4 to 12	0.015	g's	20
ADC Total Temperature	-15 to 250	0.1	deg C	10
N/B Sideslip Angle	±25	0.003	deg	40
N/B Angle of Attack	-10 to 40	0.005	deg	40
L/H Brake Pedal Force	0 to 300	0.2	lbs	10
R/H Brake Pedal Force	0 to 300	0.2	lbs	10
L/H Rudder Pedal Force	0 to 150	0.4	lbs	40
R/H Rudder Pedal Force	0 to 150	0.4	lbs	40
L/H Rudder Pedal Pos.	±5	0.01	in	40
R/H Rudder Pedal Pos.	±5	0.01	in	40
Lateral Stick Position	±4.5	0.01	in	40
Longitudinal Stick Pos.	-3 to 6	0.01	in	40
L/H Stabilator Position	-30 to 15	0.05	deg	10
R/H Stabilator Position	-30 to 15	0.05	deg	10
L/H Rudder Position	±30	0.05	deg	10
R/H Rudder Position	±30	0.05	deg	10
L/H Aileron Position	±20	0.04	deg	10
R/H Aileron Position	±20	0.04	deg	10
Pitch Rate	±30	0.07	deg/sec	10
Roll Rate	±250	0.8	deg/sec	10
Yaw Rate	±30	0.08	deg/sec	10
ADC True Airspeed	0 to 2500	0.1	kts	10
ADC Pressure Altitude	0 to 80,000	1.3	ft	10
ADC Calibrated Airspeed	0 to 1000	0.06	kts	10
Mach Number	0.1 to 3	0.0002	--	10
ADC Angle of Attack	-10 to 40	0.01	deg	10
INS Pitch Angle	±180	0.02	deg	10
INS Roll Angle	±180	0.02	deg	10
INS E/W Velocity	±4000	0.1	ft/sec	10
INS N/S Velocity	±4000	0.1	ft/sec	10
INS True Heading	±180	0.02	deg	10
INS Altitude	0 to 80,000	1.3	ft	10
INS Rate of Climb	±2000	0.13	ft/sec	10
INS E/W Acceleration	±250	0.25	ft/sec^2	10
INS N/S Acceleration	±250	0.25	ft/sec^2	10
INS Vertical Accel.	±500	0.25	ft/sec^2	10
Data Run Number	0 to 1000	--	--	10
Pilot Voice	--	--	--	20,000
Total Fuel Quantity	0 to 25,000	25.0	lb	10

Table 4. Stability and Control Derivative Descriptions and Expected Accuracies Using MMLE Method

Derivative	Name	Expected Accuracy (Pct)	Contributing Factors(s)	Sign for Stability; Comments
(Primary)				
$C_{m\alpha}$	Long Static (Pitch) Stability	±7.5	Wing, Horiz. Tail, cg	(-); Most important long stability deriv
$C_{m\delta e}$	Elevator Power	±7.5	Elevator, Wing, cg	(+); Very Important for long control
$C_{N\alpha}$	Normal Force Slope	±7.5	Wing	(+); Effects long short period damping
$C_{l\beta}$	Dihedral Effect	±7.5	Wing, Tail	(+); Very important for lat stability
$C_{l\delta a}$	Lateral (Roll) Control Power	±7.5	Differential lat surfaces	(+); Most important lat-dir control deriv
$C_{n\beta}$	Directional Stability	±7.5	Vert Tail	(+); Very important for lat-dir stability
$C_{n\delta r}$	Rudder Power	±7.5	Rudder	(+); Very important for dir control
(Secondary)				
C_{mq}	Pitch Damping	±15	Wing, Horiz Tail, cg	(-); Very important for long stability
C_{lp}	Roll Damping	±15	Wing, Tail	(-); Important for lat-dir stability
$C_{n\delta a}$	Adverse (or Proverse) Yaw	±15	Differential lat surfaces	(+); Causes A/C to yaw opposite turn
$C_{y\beta}$	Side Force Damping	±15	Vert Tail, Fueselage	(-); Important for Lat stab, engine out

Table 4. Continued

Derivative	Name	Expected Accuracy (Pct)	Contributing Factors(s)	Sign for Stability; Comments
(Transitional - Aircraft Dependent)				
$C_{N\delta e}$	Normal Force Change w/ Elev	±25	Horiz Tail, Canard	(-); For tail-to-rear A/C, negligable
$C_{l\delta r}$	Roll Due to Rudder	±25	Rudder	(-); Little effect on lat-dir stability
C_{np}	Yawing Moment Change w/ Roll Rate	±50	Wing, Vert Tail	(+); Fairly important in lat-dir dynamics
C_{nr}	Yaw Damping	±50	Vert Tail, Fues, Wing	(-); Very important in lat-dir stability
$C_{y\delta r}$	Side Force Change w/ Rudder	±25	Rudder	(-); Relatively unimportant
C_{lr}	Rolling Moment Change w/ Yaw Rate	±200	Vert Tail, Wing	(+); Secondary importance to lat-dir stab
$C_{y\delta a}$	Side Force Change w/ Aileron	±100	Differential Lat surfaces	(+); May be important for highly swept, "rolling tail" A/C

Table 5. Flight Test versus Flight Manual Takeoff Comparison for Twin Engine Fighter Configuration

Sea Level - Standard Day - No Wind

Gross Weight (Lb)	Flt Manual Takeoff Speed (KCAS)	Distance-to-Takeoff (ft)			Distance-to-50 Ft AGL (ft)		
		Flt Manual	Flt Test[b]	Diff (Pct)[c]	Flt Manual	Flt Test[b]	Diff (Pct)[c]
40,000	146	900	1070	-12.6	1800	2750	-52.8
45,000	159	1270	1390	- 9.4	2230	3150	-41.3
50,000	172	1640	1810	-10.4	2760	3670	-33.0
53,300	181	1930	2160	-11.9	3180	4100	-28.9
56,000	183	2120	2290	- 8.0	3450	4240	-22.9
60,000	189	2490	2600	- 4.7	3920	4560	-16.3

a All tabular values are representative of actual results. Percentage differences are actual.

b Flight test data generated from takeoff performance model.

c Diff (Pct) = $\left[\frac{Flt\,Manual - Flt\,Test}{Flt\,Manual}\right] * 100\%.$

Table 6. Flight Test versus Predicted Drag Comparison Summary for Variable Wing Sweep, Multi-Engine Long Range Combat Aircraft Configuration

Wing Sweep (deg)	Pressure Altitude (ft)	Mach Number	W/δ (lb)	C_L[a]	C_D[a] Predicted	Flt Test	Diff[b] (Pct)
25	30,500	.72	950,000	.59	.0313	.0328	- 4.8
	23,500	.72	950,000	.59	.0309	.0324	- 4.9
25	21,600	.70	700,000	.46	.0244	.0278	-13.9
67	0	.85	300,000	.13	.0219	.0219	0.0
55	0	.55	240,000	.25	.0204	.0227	-11.3
20 PA	0	.40	220,000	.45	.1229	.1037	+15.6

a Tabulated values for C_L and C_D are representative of actual results. Percentage differences are actual.

b Diff (Pct) = $$\left[\frac{C_{D_{predicted}} - C_{D_{flt\ test}}}{C_{D_{predicted}}}\right] * 100\%.$$

Table 7. Flight Test versus Flight Manual Range Factor Comparison for Twin Engine Fighter Configuration

Standard Day Conditions

	W/δ = 60,000 lb Altitude = 10,000 ft F/M Opt Range Mach No. = 0.50					W/δ = 180,000 lb Altitude = 35,000 ft F/M Opt. Range Mach No. = 0.76				
	Optimum Range Mach No.		Optimum Range Factor (NAM)			Optimum Range Mach No.		Optimum Range Factor (NAM)		
Loading No.	Flt[b] Test	Diff	Flt Manual	Flt[b] Test	Diff[c] (Pct)	Flt[b] Test	Diff	Flt Manual	Flt[b] Test	Diff[c] (Pct)
1	.49	0.01	2575	2465	4.3	.80	-0.04	4505	4410	2.1
2	.49	0.01	2530	2420	4.3	.79	-0.03	4370	4285	2.0
3	.49	0.01	2465	2355	4.5	.79	-0.03	4230	4170	1.4
4	.49	0.01	2270	2175	4.2	.79	-0.03	3820	3835	-0.4
5	.48	0.02	2005	1925	4.0	.77	-0.01	3215	3335	-3.7

a All tabular values are representative of actual results. Percentage differences are actual.

b Flight test data generated from the DPS.

c Diff (Pct) = $\left| \frac{Flt\,Manual - Flt\,Test}{Flt\,Manual} \right| + 100\%.$

Table 8. Flight Test versus Flight Manual Landing Comparison for Twin Engine Fighter Configuration

Sea Level - Standard Day - No Wind

		Landing Ground Roll (ft) Aero-braking[b]			Landing Ground Roll (ft) Full Anti-Skid Braking[c]		
Gross Weight (lb)	Touchdown Speed (KCAS)	Flt Manual	Flt[d] Test	Diff[e] (Pct)	Flt Manual	Flt[d] Test	Diff[e] (Pct)
30,000	122	3920	3810	2.8	2920	2740	6.2
35,000	135	4770	4740	0.6	3390	3210	5.3
40,000	147	5830	5660	2.9	3820	3700	3.1
45,000	158	6730	6590	2.1	4240	4190	1.2
50,000	169	7630	7700	-0.9	4770	4690	1.7

a All tabular values are representative of actual results. Percentage differences are actual.

b Aerodynamic braking down to 70 KCAS followed by full anti-skid braking.

c Full anti-skid braking applied after touchdown.

d Flight test data generated from landing performance model.

e Diff (Pct) = $\left| \frac{Flt\,Manual - Flt\,Test}{Flt\,Manual} \right| * 100\%.$

VITA

Steven Herzig was born in Los Angeles, California, on August 23, 1960. He attended Simi Valley High School in Simi Valley, California and graduated in June 1978. In July of 1978 he began his Air Force career at the United States Air Force Academy in Colorado Springs, Colorado. He graduated from the Air Force Academy in June of 1982, receiving his commission as an officer in the US Air Force. At that time he was also awarded a Bachelor of Science degree in Aeronautical Engineering.

In July of 1982, he was assigned as a Flight Test Engineer to the United States Air Force Flight Test Center at Edwards Air Force Base, California. From 1982 until May 1986, he served as Performance and Flying Qualities Engineer on the F-15E and B-1B test programs. In May 1986 he was assigned as an Aeronautical Systems Project Manager at Arnold Engineering Development Center, Arnold Air Force Base, Tennessee. While at Arnold Air Force Base, he continued his studies at the University of Tennessee Space Institute at Tullahoma, Tennessee, receiving a Master of Science degree in Aerospace Engineering in August 1990.

Capt. Herzig is married to the former Jennifer Lynn Wickliff of Indianapolis, Indiana and has two children.