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Flight-Test Techniques Employed to Successfully Verify F/A-18E In-Flight Lift and Drag

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F/A-18E flight results successfully confirmed preflight aerodynamic and performance predictions. Because this was achieved very early in the flight-test program, the need to rely heavily on flight data to characterize aircraft performance capabilities was significantly reduced. The original aircraft performance flight evaluation plan was reduced by 60 flights with obvious cost benefits. This was a direct result of early flight test planning by a working group composed of representatives carefully selected from the involved organizations. Flight-test techniques were developed to determine high-quality, in-flight lift and drag data and to directly demonstrate aircraft performance capability. These techniques are disscussed and a successful correlation of preflight predictions and early flight results is presented.

Nomenclature

D_{AFT}	= afterbody drag, lb
D_{ECS}	= Environmental Control System heat exchanger drag, lb
D_{RAM}	= ram drag, lb
D_{SPILL}	= spill drag, lb
FG	= gross thrust from selected in-flight thrust method, lb
GW	= aircraft gross weight, lb
Nx_{WCG}	= longitudinal acceleration at the c.g. in the wind axis from selected source, g
Nz_{WCG}	= normal acceleration at the c.g. in the wind axis from selected source, g
Q	= dynamic pressure, psf
S	= wing reference area, ft^2
α	= angle of attack, deg
β	= angle of sideslip, deg
$\Delta C_{D_{Mach}}$	= drag correction to desired Mach number
$\Delta C_{D_{RN}}$	= drag correction to reference altitude
$\Delta C_{L_{CG}}$, $\Delta C_{D_{CG}}$	= correction to reference c.g. position
$\Delta C_{L_{Flap}}$, $\Delta C_{D_{Flap}}$	= correction to nominal flap schedule
$\Delta C_{L_{Trim}}$, $\Delta C_{D_{Trim}}$	= correction to trim condition
ε	= engine cant angle, deg

Introduction

THE flight-test program featured early planning by a working group composed of representatives from the involved organizations. Frequent meetings were convened to ensure clear communication. The ultimate goal of the working group was to verify guaranteed aircraft performance. As set forth in program requirements, isolation of airframe and propulsion system contributions to total vehicle performance was to be accomplished. A credible lift and drag database was to be developed through in-flight thrust determination. This database was then combined with customer-specified minimum engine performance characteristics and demonstrated mass properties to calculate aircraft performance. Calculated performance is used to demonstrate compliance with contract performance guarantees. This approach was specified in lieu of a formal performance demonstration to isolate the responsibility for any performance variance. However, performance demonstration data were available from lift and drag test maneuvers. This paper highlights the techniques used to determine F/A-18E flight-derived drag characteristics and presents a correlation of wind-tunnel-predicted drag[1] and performance with early flight results.

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Flight-Test Program

The F/A-18E flight test program began in November 1995 with the first flight of F/A-18E1. The test program featured five single-place F/A-18E aircraft and two dual-place F/A-18F aircraft each with a specific role in the test program. The test vehicle for propulsion and performance flight test was the second F/A-18E development aircraft, designated E2 (Fig. 1), which began flight testing in December 1995. With the exception of a noseboom, E2 was fully representative of a production aircraft with all of the production external surface treatments to eliminate any adjustments to account for test to production differences.

Force and Moment Accounting Procedure

Per the F/A-18E force and moment accounting procedure, all of the force components that are independent of engine power setting are included in the aircraft lift and drag characteristics. All of the factors that affect the engine cycle performance and all of the force components that are functions of engine throttle setting and exhaust system geometry are included in the installed propulsion system performance. Components of the wind-tunnel force and moment accounting procedure[1] were used to collapse flight-derived lift and drag to a set of aerodynamic reference conditions and to nominal test conditions as indicated by Fig. 2.

Lift and Drag Equations

The equations used to derive lift and drag coefficients from flight data are defined hereafter.
The lift and drag coefficients at test conditions are

$$C_{L_{TESTDAY}} = [(-FG) * \sin\alpha * \cos(\varepsilon) + Nz_{WCG} * GW]/S * Q \quad (1)$$

$$C_{D_{TESTDAY}} = [(FG) * \cos\alpha * \cos\beta * \cos(\varepsilon) - D_{RAM} - D_{SPILL} - D_{ECS} - D_{AFT} - Nx_{WCG} * GW]/S * Q \quad (2)$$

The lift and drag coefficients at reference conditions are

$$C_{L_{REF}} = C_{L_{TESTDAY}} + \Delta C_{L_{CG}} + \Delta C_{L_{Flap}} + \Delta C_{L_{Trim}} \quad (3)$$

$$C_{D_{REF}} = C_{D_{TESTDAY}} + \Delta C_{D_{RN}} + \Delta C_{D_{CG}} + \Delta C_{D_{Flap}} + \Delta C_{D_{Trim}} + \Delta C_{D_{Mach}} \quad (4)$$

Test Maneuvers

Three classes of maneuvers[2] were used to establish the aerodynamic database: steady-state, quasi-steady-state, and dynamic. Steady-state maneuvers (cruises, sustained turns) yield the most accurate data but require a large amount of flight time (e.g., 1-min stabilization and 3-min data acquisition time for cruise) and airspace to define one point on the drag polar (Fig. 3). Quasi-steady-state maneuvers (accelerations, constant Mach climbs) provide more drag polar definition (Fig. 4) with extremes in throttle setting to verify force and moment accounting procedures. However, uncertainty is increased relative to steady-state maneuvers. Dynamic maneuvers (roller coasters, constant Mach windup turns) allow evaluation of aerodynamic characteristics covering a range of angles of attack that cannot be achieved through steady-state or quasi-steady-state maneuvers (Fig. 5). However, data synchronization is required to reduce the large data scatter that may result from time skew between various measurements. Dynamic maneuvers were performed within the constraints of steady-state engine operation. Consequently, dynamic in-flight thrust techniques were not implemented.

Planning

Working Group Approach Started Early

The working group convened 32 months prior to flight testing. success depended heavily on coordinating and executing the preflight activities. Once flight testing began it would be difficult to adopt new techniques or methods. Lessons learned during previous test programs were addressed to develop techniques that would ensure a successful and efficient program. Required resources were then defined and acquired. The group then developed an integrated

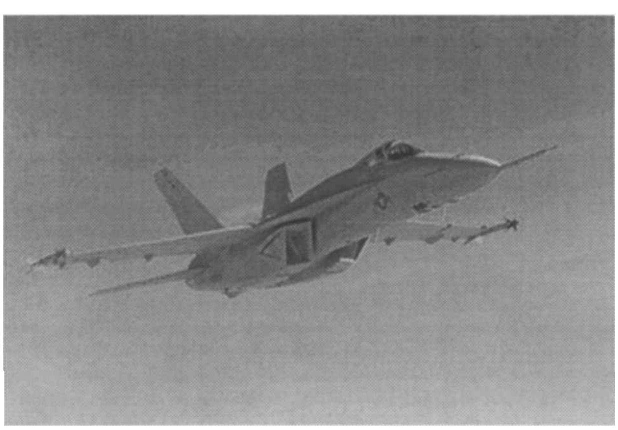

Fig. 1 Performance flight-test vehicle, F/A-18E2.

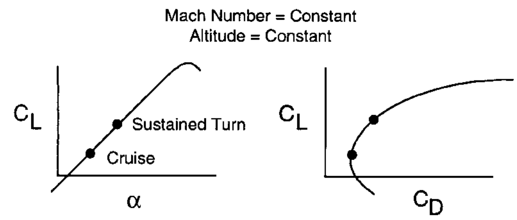

Fig. 3 Steady-state maneuver database coverage.

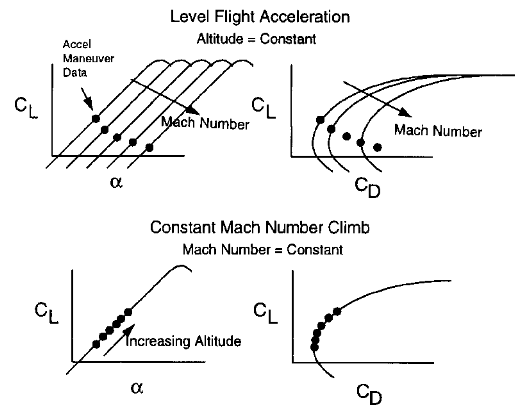

Fig. 4 Quasi-steady-state maneuver database coverage.

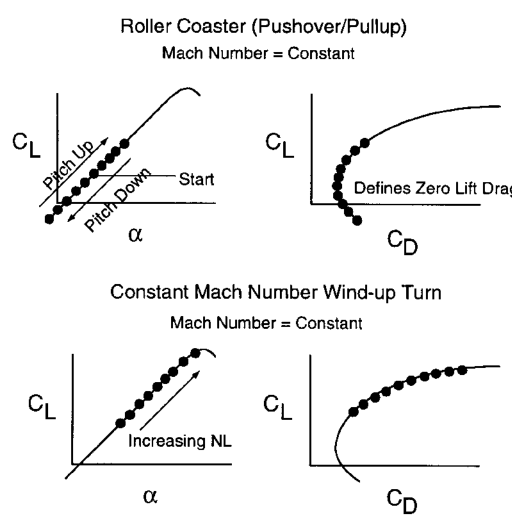

Fig. 5 Dynamic maneuver database coverage.

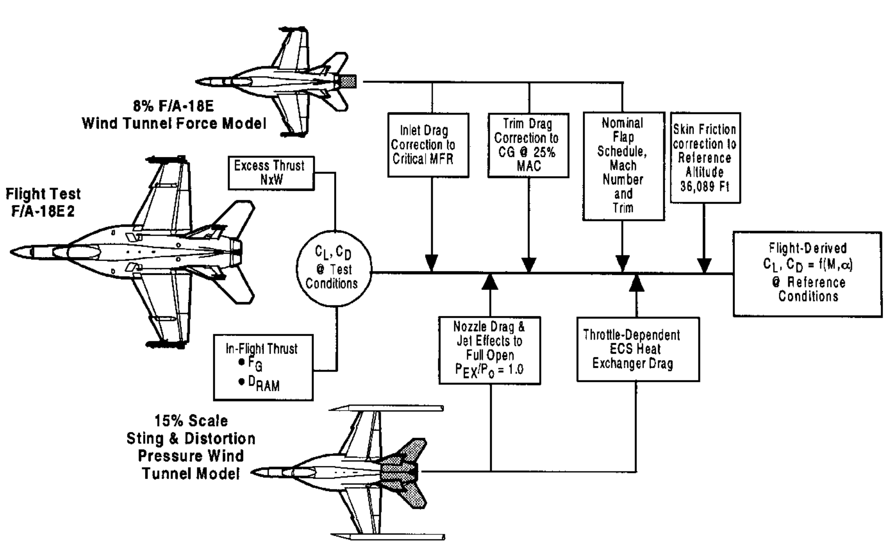

Fig. 2 Force and moment accounting procedure.

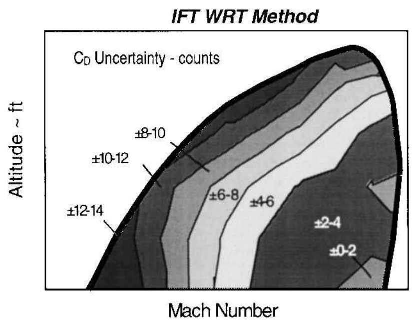

Fig. 6 Drag coefficient uncertainty at thrust required conditions.

program plan that defined milestones and assigned specific tasks to the member organizations. Members of the group communicated on a daily basis and quarterly meetings were convened to review progress and to establish corrective actions where required.

Preflight Uncertainty Analysis

Uncertainty analysis became a common thread of all of the preflight tasks. Equations, methods, instrumentation, and the test matrix all required preliminary definition before this analysis could begin. The working group adopted Ref. 3 as a guide. A phased analysis approach was used. The first phase defined the critical measurements. The second phase produced judgmental information to assess the acceptability of the uncertainties. Data reduction procedures were documented in an easily understood report format to ensure clear communication between working group members. Uncertainties for every input to the data reduction process were determined. The hierarchy of fundamental error sources was established to determine if a significant improvement in a measurement uncertainty should be pursued or if redundant measurements or methodologies were required. A comprehensive analysis was conducted for all maneuver types over a range of flight conditions. Figure 6 is a typical summary of drag coefficient uncertainties. This information was used to understand trends with flight conditions. The primary products of the uncertainty analysis were test matrix optimization, instrumentation preflight go/no-go criteria, data validity criteria, data acquisition system cost justification, and end-to-end validation of the actual data processing system.

Test Matrix Influenced by Uncertainty Analysis

On completion of the uncertainty analysis, a test matrix to construct an aerodynamic database was defined. The basic philosophy was to anchor absolute drag levels with the highest confidence points, steady-state maneuvers, and then to use quasi-steady-state and dynamic maneuvers to establish trends due to variations in angle of attack and Mach number. Repeat points were included in the matrix based on increased uncertainty prevalent at certain flight conditions and to increase confidence at key performance specification points.

Utilized Manned Flight Simulator

Prior to flight, the test pilots evaluated the maneuvers in the crewed flight simulator. The simulations highlighted unexpected effects due to flight control system lag filters that were incorporated to mitigate gust response. This led to implementation of a flight control option to selectively bypass these lag filters for designated maneuvers. Other benefits included improvements to maneuver techniques, revisions to maneuver tolerances, pilot familiarization, and identification of conditions where flight control system hinge moment limits are encountered. These benefits enhanced data quality and significantly reduced flight time associated with test technique development.

In-Flight Thrust (IFT) Model Development

The engine manufacturer was responsible for development of the cycle computer program, or deck, that models the performance of the F414 flight-test engine configuration. This cycle deck included the capability to calculate in-flight thrust (IFT) by two independent methods. The cycle deck is a thermodynamic model of the engine. In the IFT operation mode, the cycle deck thermodynamically iterates each engine component to match the flight-test measured input data. Gross thrust is then calculated from the thermodynamic solution.

Two Independent In-Flight Thrust Methods

Two in-flight thrust methods were used. These were variants of the force area pressure and airflow root temperature methods of Ref. 4. The methods were sensitive to different engine parameters allowing for two independent IFT calculations. This would provide high confidence in the results when the methods agreed with each other. To support the IFT computation methods, the flight test engines were fully instrumented with gas path parameters.

Preflight Altitude Test Cell Calibration

Altitude test cell data for three F414 engines were acquired at Arnold Engineering Development Center (AEDC) to support IFT model development. Inlet pressure and airflow and afterburner inlet conditions and performance are the key drivers in determining IFT. Consequently, the inlet rake and afterburner modules from the two flight-test engines plus a spare were calibrated in the test cell. These tests were designed to duplicate aircraft performance testing within the altitude test facility where thrust is physically measured using a load cell. IFT methodology correlations were then developed to minimize the error between the calculated IFT and the measured thrust at AEDC. Final correlation between measured and calculated thrust was found to be within 1.2% (2-sigma) for a large data sample acquired with the three engines.

Actual Flight Instrumentation Used in Altitude Test Cell

Using the flight hardware at the ground-test facility provided the opportunity to isolate any biases or anomalies between the ground and flight-test instrumentation and data acquisition systems. During these tests, key in-flight engine instrumentation was routed to both the actual flight test and AEDC data acquisitions systems using pneumatic and electrical tees. Fuel flow measurements produced the only significant difference between the data acquisition systems. This was attributed to the flight-test meter having a larger operating range than the ground meters. The ground-test facility featured several meters that are highly accurate over smaller flow ranges, thereby allowing the flow rate to dictate which meters are used at a given condition. Consequently, correlations to match AEDC fuel flow measurements were developed for the flight meters.

Instrumentation

Redundant Instrumentation

An overview of the airframe and propulsion system instrumentation is provided in Figs. 7 and 8, respectively. Both engines were identically instrumented. Redundant instrumentation was incorporated for all key measurements. Redundancy permitted instrumentation health tracking, isolation of faulty measurements, and the flexibility to select the best source for a particular maneuver or flight condition.

Special Preflight Calibrations

All standard calibration procedures were completed prior to flight. However, some special calibrations were also performed. An individual fuel tank calibration was conducted to reduce fuel quantity and gross weight uncertainties. The boost venturi probes used to measure engine bleed flow were also calibrated. The results indicated that the left engine produced more repeatable results. Therefore, the test procedure would be to take all of the bleed from the left engine and to turn the right bleed off. A pneumatic line lag test was also conducted for the noseboom pitot pressures and key engine pressures (turbine discharge total pressures and nozzle inlet static pressures). An Inertial Navigation System rate table calibration was performed to select the most accurate unit available and to isolate any biases.

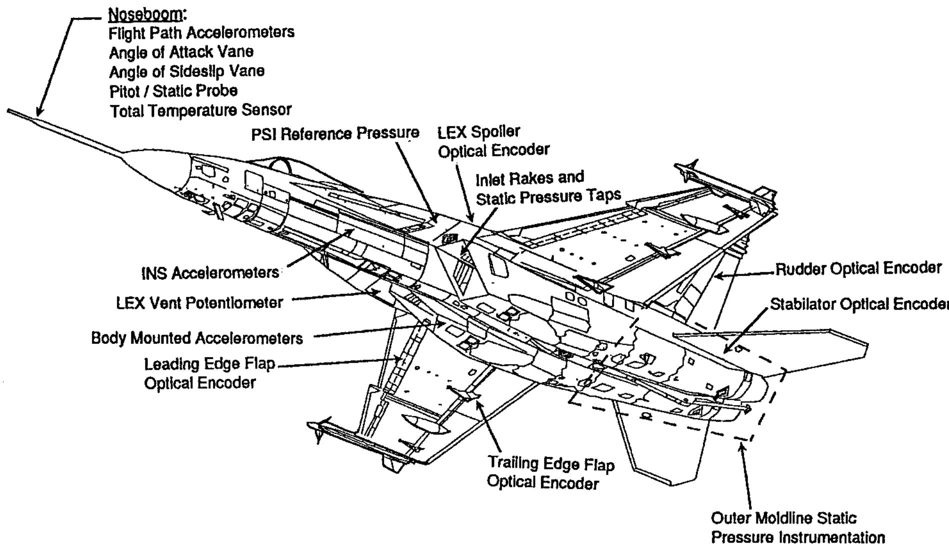

Fig. 7 F/A-18E2 performance flight-test instrumentation.

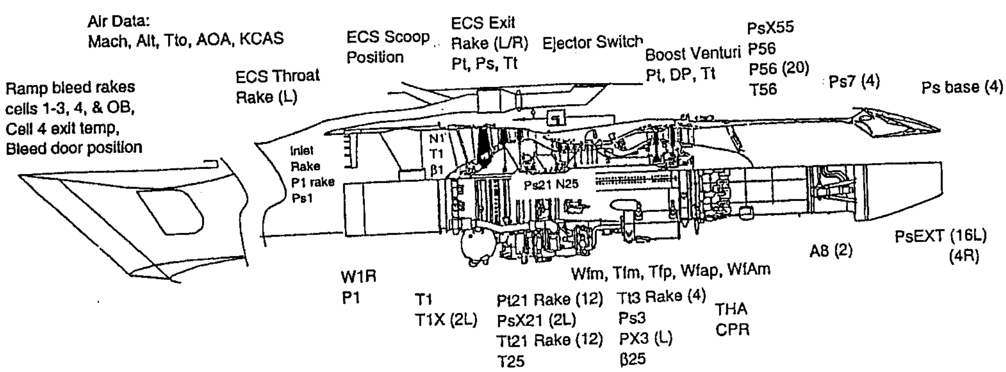

Fig. 8 F/A-18E2 IFT engine instrumentation.

Table 1 Test program phasing

Test phase	Program percentage
Noseboom pitot-static calibration	1.4
Early methodology verification	3.6
Flap schedule verification	6.1
Configuration development testing	46.2
Basic aircraft lift and drag documentation	16.6
Store effects documentation	18.9
Final configuration verification	7.2

Data Acquisition/Analysis

Test Program Phasing

The aircraft performance test program was divided into seven phases, each of which had a specific objective and success criteria. Success criteria were satisfied before proceeding to the next test phase. The percentage of test points that each phase required out of the total aircraft performance test program is outlined in Table 1. Early methodology verification ensured that all systems were operating properly before testing proceeded. The benefits of early planning became apparent at the start of this phase; all systems functioned properly from the first maneuver. The next phase verified that the flap schedule had been properly optimized with wind-tunnel results. After flap schedule verification, testing to document the baseline lift and drag characteristics for the basic aircraft without stores was completed. This was followed by configuration development testing, including evaluation of numerous design refinements. The end of this phase featured regression testing to reestablish basic aircraft lift and drag with changes made during configuration development.

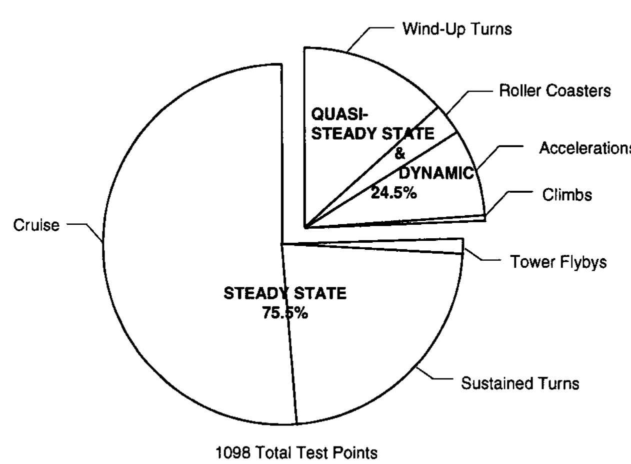

Fig. 9 Maneuver utilization.

The effect of store carriage was then evaluated for complete loadings and components thereof. Finally, all external surface features that would be present on fleet introduction aircraft were incorporated for final configuration verification.

Maneuver Utilization

All maneuver types selected prior to flight were employed successfully. Flight time was not required to optimize maneuver technique; however, maneuvers were occasionally reflown because the stringent maneuver tolerances were exceeded. The degree to which each maneuver type was utilized (Fig. 9) was guided by uncertainty analysis and pre-test predictions to visualize lift/drag characteristics yielded by each maneuver. Approximately 75% of the test points were steady-state maneuvers. Although the quasi-steady-state and dynamic maneuvers were very successful, heavy emphasis was placed on the steady-state maneuvers to achieve maximum possible data accuracy.

Time Synchronization of Measurements

Dynamic maneuvers provided an opportunity to acquire large amounts of aerodynamic data in a small amount of test time, thereby reducing flight costs. However, careful time synchronization of measurements was required. Based on uncertainty analysis results, key instrumentation was evaluated to determine time lags. Lags were determined for the entire data acquisition system starting at the sensor and ending at the data recorder, accounting for all components in between.

Enforced Tight Maneuver Tolerances

Tight tolerances were placed on the maneuvers. One of the most challenging requirements was maintaining cruise points within $\pm 0.005M$ for 3 min. Cruise data would eventually be averaged over the steadiest portion of the maneuver to eliminate the influence of random errors. Experience and uncertainty analysis showed that 3-min cruise points would typically yield enough steady data. Initially, many cruise points required several attempts to meet the tolerance criteria. However, proficiency was soon achieved with outstanding results. Enforcing tight tolerances resulted in very high-quality data that eliminated the need for repeat testing and significantly reduced the total number of flights.

Enforced Strict Instrumentation Go/No-Go Criteria

Strict instrumentation go/no-go criteria was enforced. This included 247 measurements critical for determination of lift and drag based on uncertainty analysis. Test points were not flown if any criteria were violated before or during a flight. Other testing would be done with the aircraft until the criteria were met. Adhering to these guidelines produced high data quality and reduced the total number of flights.

Real-Time Data Monitoring

Real-time telemetry displays were created to provide ground monitor personnel with all of the information required to determine maneuver acceptability in an easily interpreted format. Displays included variance from initialization point, time traces, and tabular data. The display also provided immediate visual queues as the bars and tabular data would change color when tolerances were exceeded. Additional displays provided comparisons with previous test points to assess repeatability or trends. Test efficiency was increased by enabling the engineer to quickly determine if a test point was acceptable.

Automated Analysis Tools

Efficient ways to assess data quality and analyze the data were required. Prior to testing, plot formats were defined for data quality and maneuver tolerance assessment. An automated process was developed to make these plots quickly and to view them online or on hard copy. Based on wind-tunnel data, a postprocessing routine was developed to incrementally correct the lift and drag coefficients for deviations from nominal flap schedule, trim, and target Mach number. This reduced data scatter to facilitate database development.

Wind-Tunnel Flight Comparisons

Early flight results indicated excellent agreement with preflight wind-tunnel predictions. The wind tunnel database[1] was completed more than 1 year prior to first flight. As flight testing progressed and configuration refinements were incorporated, lift and drag results continued to correlate very well for all maneuver types. Performance capabilities predicted by the preflight wind-tunnel database were verified directly with performance demonstration data. The following paragraphs present typical aerodynamic and performance data to illustrate these findings.

Lift and Drag

Figure 10 shows the variation of drag with lift over a portion of the subsonic/supersonic flight envelope at the aerodynamic reference conditions. Flight data is provided for both IFT methodologies. Excellent agreement between wind-tunnel and flight results and between IFT methodologies is demonstrated. Figure 11 shows the variation of lift with angle of attack. Again, excellent agreement is demonstrated. The flight data collapse very well for various altitudes, power settings, and maneuver types. This is an indication that the force and moment accounting system is valid, that the maneuvers were conducted properly, and that the instrumentation systems and data reduction procedures were operating properly.

Performance Demonstration Comparisons

Comparisons between preflight performance predictions and the flight demonstration data are presented. Preflight performance predictions are based on wind-tunnel results.[1] Uninstalled, predicted engine performance was determined by the engine manufacturer prior to first flight through ground testing in an altitude test cell. The airframe manufacturer determined engine installation effects. IFT determination subsequently confirmed that the predicted installed engine performance database was representative of the flight-test engines. Likewise, excellent correlation between predicted and demonstrated aircraft performance was achieved early in the test program. This provided further confidence that the successful lift and drag correlations were valid. Performance demonstration data have been adjusted to a set of standard conditions to allow a consistent comparison with pre-flight predictions. These conditions

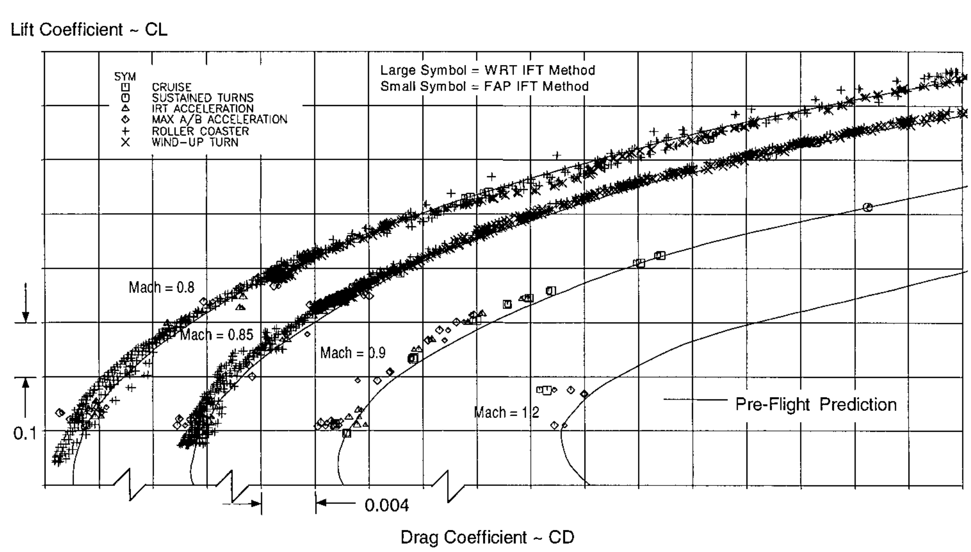

Fig. 10 F/A-18E2 flight-derived drag.

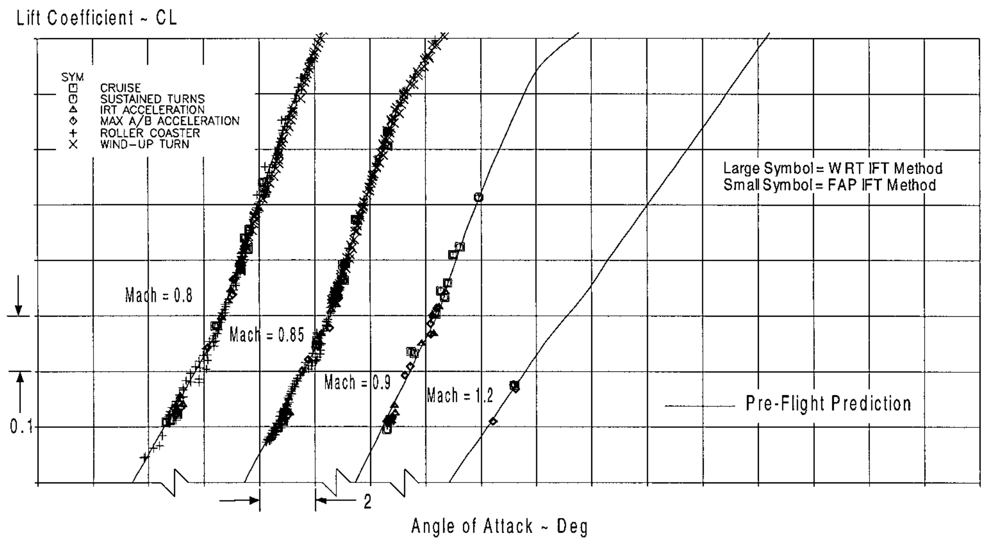

Fig. 11 F/A-18E2 flight-derived lift.

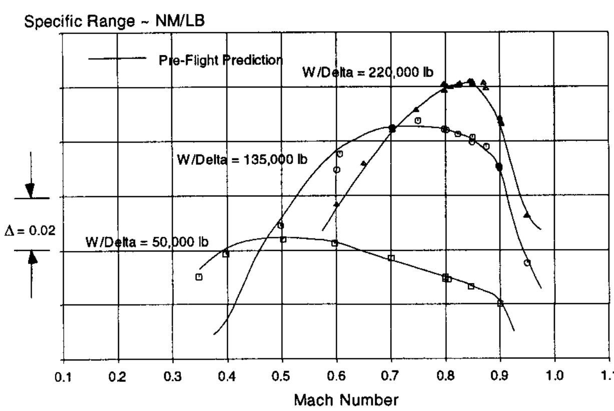

Fig. 12 F/A-18E2 cruise specific range.

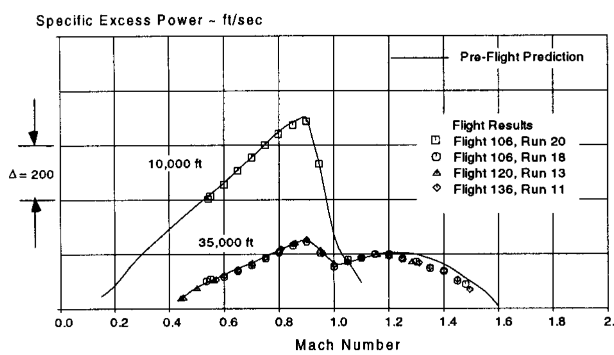

Fig. 14 F/A-18E2 maximum A/B thrust specific excess power.

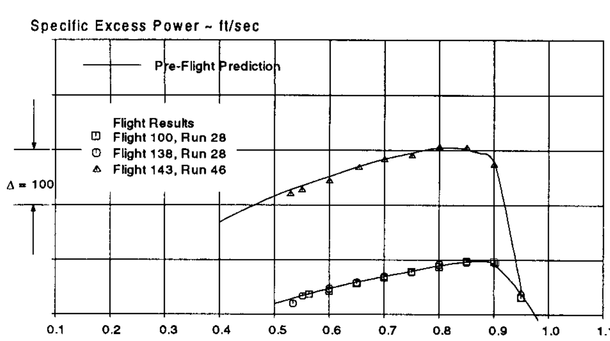

Fig. 13 F/A-18E2 intermediate thrust specific excess power.

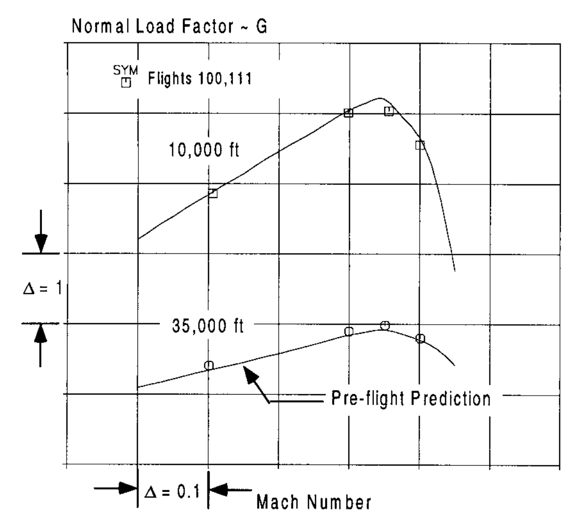

Fig. 15 F/A-18E2 intermediate thrust sustained turn load factor.

include 1) the U.S. standard atmosphere, 2) unaccelerated flight for steady-state maneuvers, 3) aerodynamic reference c.g., 4) standard or target altitude, and 5) production equipment weight at 60% fuel state.

Cruise Performance

Cruise specific range, that is, $SR = V / W_f$, provides a measure of gas mileage in terms of nautical miles per pound of fuel. Excellent correlation between predicted and demonstrated results was achieved (Fig. 12). The flight data represent a time average of typically 3 min of data.

Specific Excess Power

Specific excess power characterizes an aircraft's ability to change energy levels (i.e., climb, acceleration, pulling gs). Excellent correlation between predicted and demonstrated results was achieved, Figs. 13 and 14. The flight data were acquired from level flight acceleration maneuvers. The engines were preheated for 5 min during intermediate thrust turn maneuvers to eliminate the effect of thermal transients on aircraft performance.

Turn Performance

One measure of turn performance is the ability to sustain gs, or turn load factor N_L, in a constant airspeed level turn. Good agreement between predicted and test results was achieved, Fig. 15. The flight data represent a time average of typically 30 s of data.

Conclusions

The F/A-18E aircraft performance flight evaluation was very successful and produced uniquely high-quality data. This was not the result of new technological advancements. Conventional and accepted industry standards were employed. What made the F/A-18E program unique was the commitment to very early planning, a working group consisting of carefully selected individuals with applicable experience, commitment of resources to allow full implementation of all aspects of accepted industry IFT determination procedures, and uncompromising standards on instrumentation health and maneuver quality. Each of these aspects required increased initial cost investments. However, significantly reduced flight-test costs substantiated that up-front investment is crucial.

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