Recent Flight Experience with the F100 Engine in the YF-16

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Success of the YF-16 flight program conducted in austere budget environment can be attributed partly to the outstanding performance of the propulsion system. The Pratt & Whitney Aircraft F100-PW-100 engine operated satisfactorily throughout the flight envelope. Although the scope of the inflight measurements was limited by cost, sufficient data were acquired for monitoring engine operation and for input to the Air Force Uniform Flight Test Analysis System (UFTAS). Concise programing of engine cycle and inflight thrust computation procedures (PROP) permitted the incorporation of PROP into UFTAS and, thus, the reduction of propulsion data with minimal effort. The test and predicted thrust data show agreement from the standpoint of flight test computations, engine predictions, test stand measurements, and airplane drag predictions.

Nomenclature

A_0/A_i = inlet capture area ratio
A_j = exhaust nozzle throat area
alt = pressure altitude
C_d = exhaust nozzle discharge coefficient
C_g = gross thrust coefficient, $C_v C_d$
ΔC_g = gross thrust correlation factor
CIVV = fan inlet variable camber vanes
C_v = exhaust velocity coefficient
D_e = exhaust nozzle exit diameter
ECS = environmental control system
EEC = engine electronic control
F_g = gross thrust
F_{g_i} = ideal gross thrust
$F_{g_{ift}}$ = gross thrust from in-flight thrust computation procedure
$F_{g_{meas}}$ = measured gross thrust (test stand)
FM = frequency modulated
F_{n_s} = net thrust corrected to baseline
FTIT = fan turbine inlet temperature
IIRS = instrumentation inertial reference set
M_0 = aircraft Mach number
N_1 = fan speed
N_2 = high-pressure-compressor speed
Pamb, P_0 = ambient pressure
p_b = burner pressure (high-pressure-compressor discharge)
PCM = pulse code modulation
p_{f_0} = engine inlet fuel pressure
p_{t_6} = fan/turbine discharge mixed total pressure
p_{t_7} = exhaust total pressure
PLA = power lever angle
RCVV = high-pressure-compressor variable stators
SC = signal conditioner
TM = telemeter
T_{t_0} = freestream total temperature
T_{t_2} = engine inlet total temperature (equal to T_{t_0})
UFC = unified fuel control
UFTAS = uniform flight test analysis system
VCO = voltage controlled oscillator
W_{f_e} = fuel flow to engine interburners
W_{f_t} = total fuel flow to engine, including augmentor
α = pitch angle of attack
β = yaw angle of attack
γ = specific heat ratio
δ = p_{amb}(psia)/14.696

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Introduction

THE basic approach to propulsion system development provided one of the keys to the success that the YF-16 is currently enjoying. This approach differed from recent fighter development experience. Four of the last five high-performance fighter aircraft used engines that were developed specifically for and concurrently with those airplanes. Contrary to this approach, General Dynamics, at the start of the YF-16 program, selected an engine already in an advanced state of development—the Pratt & Whitney F100-PW-100. According to the contract ground rules, General Dynamics was to use the current version of this engine, i.e., no configuration changes from the engine used on the F-15. However, in line with the Air Force prototype concept, the YF-16 airframe design was developed with a great deal of engineering freedom. Experience now shows that, with this freedom, a production engine in its later development phases can be successfully integrated into a new airplane design with minimum airplane/engine interface problems.

The YF-16 is a single-engine multirole tactical fighter with a primary mission of air superiority and a good air-to-ground capability. Its wing span is 30 ft and its length is 46.5 ft. The average combat weight is about 18,000 lb, with a normal takeoff gross weight of just over 20,000 lb with internal fuel. External fuel tanks permit the total fuel load to be more than double the internal fuel load. The cockpit is set quite high, providing the pilot with a practically unobstructed view to the front, sides, and rear. (The pilots have commented that it is a simple matter for them to observe their own contrail.)

The two-airplane YF-16 program began in May 1972. It was a program built around limited funds. Only three F100 engines were ordered for the program, one for each airplane and one spare. Not quite 2½ years later, the YF-16 flight test program is practically completed, using only those three engines. The propulsion system had performed remarkably well. In the not quite nine months of flying at the Air Force Flight Test Center (AFFTC) at Edwards Air Force Base, Calif., a very sizable amount of propulsion data had been accumulated. This had been achieved in spite of the austere test program because of the high flight rate on the airplanes and because the data analysis program was planned to take full advantage of the flight test data analysis systems of AFFTC.

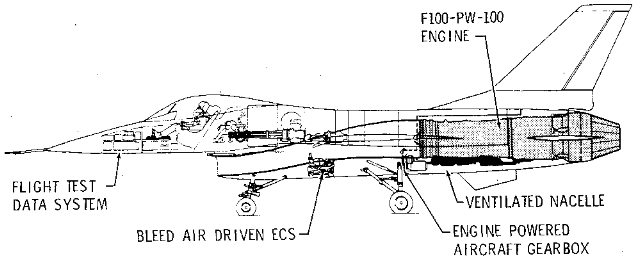

Fig. 1 Inboard profile of YF-16 showing engine installation.

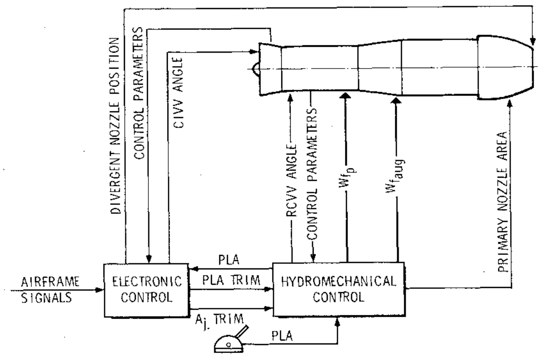

Fig. 2 F100-PW-100 control schematic.

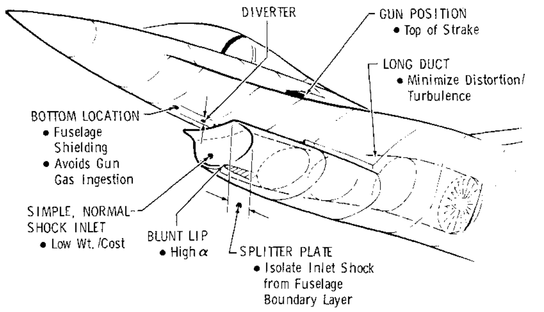

Fig. 3 Inlet design features.

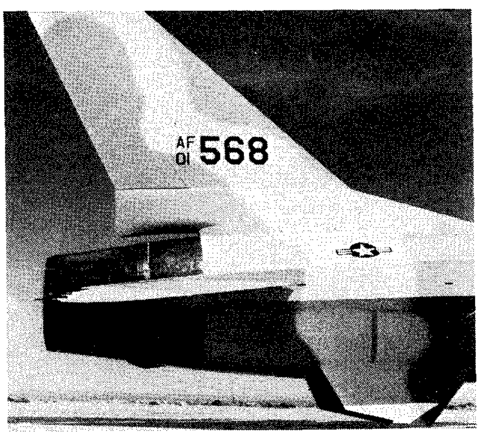

Fig. 4 Aft fuselage and exhaust nozzle.

An important characteristic of the YF-16/F100-PW-100 program has been the informal relation and cooperation between General Dynamics and Pratt & Whitney engineers. Persistent engineering coordination and open working agreements have resulted in good prediction of the propulsion system performance. The YF-16 propulsion system is operating well, and its performance matches predictions.

In this paper, the YF-16 propulsion system is described, the data acquisition/processing procedures and the data analysis programs are discussed, and some of the test reaults are presented to substantiate the success of the program.

Propulsion System Summary

The YF-16 engine, as shown in Fig. 1, is the interim production F100-PW-100. The engine is identical in configuration with the F-15 engine except for four small covers over unused anti-icing bleed ports and some longer bolts to permit attachment of the exhaust nozzle transition fairing.

The F100 is a 25,000-lb thrust class, afterburning, twin-spool turbofan with variable geometry. Compressor inlet variable-camber vanes (CIVV) are located at the fan inlet, and rear compressor variable-angle vanes (RCVV) are at the high-compressor inlet and first two stages. Advanced materials make the F100 a very light engine for its rating. The engine high thrust/weight ratio in the small YF-16 has resulted in outstanding aircraft performance.

The pilot commands the engine by a single throttle handle located on the left-hand wall of the cockpit. The engine fuel flow, variable compressor vanes, and exhaust nozzle (Fig. 2) are controlled in turn by a unified hydromechanical fuel and exhaust nozzle control (UFC), which is supervised by an engine electronic control (EEC). With the exception of the CIVV, the UFC performs the actual controlling task but with the levels trimmed by the EEC to satisfy schedules that are built into the EEC.

A simple, normal-shock inlet located under the center fuselage supplies air to the engine (Fig. 3). The inlet shielding by the forward fuselage provides increased pressure recovery during supersonic maneuvers at high aircraft angle of attack. Flow losses, turbulence, and flow distortion at the fan inlet are minimized by the relatively long inlet duct with large radius turns. The inlet features a diverter arrangement to prevent fuselage boundary-layer air from entering the inlet. A short wrap-around splitter plate isolates the normal shock from the fuselage boundary layer. The lower lip is carefully contoured to provide good flow characteristics at high angle of attack. The location of the nose landing gear aft of the intake plane greatly reduces the possibility of foreign object damage from debris on the runway.

The nacelle is ventilated by unidirectional flow both on the ground and at all conditions in flight. Air is taken on board by two ram-air scoops on the lower fuselage sides just forward of the engine and is discharged through three ports at the back near the engine exhaust nozzle. One of the three exit ports is located at each of the aft edges of the horizontal and vertical tail roots. When the landing gear is extended, nacelle airflow is pumped by bleed-air ejectors located in the exit ports.

The engine exhaust nozzle is a fully variable convergent-divergent "balanced beam nozzle." Great care was taken in defining the aircraft afterbody lines that lead up to the nozzle so as to achieve a low base drag. A very smooth contour is formed by a transition fairing that is attached to the engine and slips inside the fuselage at the fuselage aft end (Fig. 4). The configuration is designed to prevent flow separation on the fuselage afterbody and to take advantage of recompression on the back part of the nozzle, thereby providing low drag.

Compressor discharge and intermediate-stage bleed air is supplied to the aircraft environmental control system (ECS). Compressor discharge bleed also powers an air motor to position the exhaust nozzle. In addition, the engine provides mechanical shaft power which drives the aircraft hydraulic pumps and generator through an aircraft-mounted gearbox. The engine is started on the ground by turning the high-pressure compressor rotor with an ordinary air turbine starter through the same gearbox and shaft.

Propulsion Test Program

The objective of the propulsion flight test program was to check the engine operation in progressive steps to eliminate concern for unanticipated occurrences. Safety of flight was a prime consideration. Our goal in these progressive clearance steps was to give the pilot complete freedom of engine usage during air combat maneuvers throughout the YF-16 flight envelope. Thus, the approach was to plan and conduct a propulsion system operation flight test program that was aimed at checking the engine stability and transient capability both in 1g flight and during maneuvers. Some data for analysis of propulsion system performance were obtained as a fallout from these tests, but the most important propulsion performance data were obtained during the airplane performance and aerodynamic tests.

By judicious selection of the propulsion measurements, the objectives of the propulsion flight test program, including thrust determination, were achieved at very low cost. The propulsion system instrumentation (Fig. 5) was much less extensive than normally found on high-performance flight test airplanes containing afterburning turbofan engines. The selected instrumentation has acceptable accuracy and employs state-of-the-art, off-the-shelf components that did not require development.

Out of a total of 12 measurements on the propulsion system, only four were specifically for operational diagnostics: N_2, FTIT, p_b, and RCVV angle. Although the other eight measurements were also used for diagnostics work, seven of these were necessary for propulsion performance analysis, i.e., in-flight thrust determination and fuel-flow measurement. In addition, the airplane air data system provided the altitude, Mach number, ram air temperature, and angle-of-attack data needed for propulsion performance analysis.

The turbine/fan discharge mixed-flow total pressure p_{t_6}, is measured with the bill-of-material five-port rake supplied with the engine, which provides a single mixed pressure. Pratt & Whitney experimental engine tests comparing the output of this rake with those of a 30-probe test rake showed good correlation, thus permitting the use of a single transducer to generate a single signal for p_{t_6}.

Data Recording and Processing

The on-board data system for the YF-16 consists of a hybrid FM and PCM system incorporating a pilot-commanded 1-in., 14-track, 80-channel magnetic tape; a two-link PCM/FM/FM "L" band telemetry (TM) system; and signal-conditioning equipment and signal source equipment. As in the case of the instrumentation, the data system employs state-of-the art, off-the-shelf components with no new development required. No special data recording requirements were imposed by any of the propulsion-related parameters.

Ground test control via voice communication and continuous ground monitoring of the TM signal are accomplished at either or both the AFFTC Flight Test Control Center and the General Dynamics Flight Test Facility housed in a mobile unit. Of the 40 channels of real-time brush recorder display at each facility, normally eight propulsion parameters are displayed for flight surveillance (PLA, RCVV, N_2, A_j, CIVV, FTIT, p_b, p_{f_0}). Provisions are also available for continuous recording on tape of all measured parameters being transmitted on TM.

Postflight processing of data is handled through the Air Force Computing Center. The airborne data tape is the primary source for all postflight processing. However, it is supplemented as necessary by the ground-recorded TM tape to obtain backup data or data from those events where the airborne system is not activated. Standard first-generation processing procedures are available at the Computing Center for brush recording strip charts (quick look) sampling, analog-to-digital conversions, PCM decommutation, and conversion to engineering units (ADAS). Every flight of the YF-16 is processed through the Computing Center. Normally, quick-look data and ADAS data are generated for all data recorded on the airborne data tape. Engineering data are provided in listed format at a sampling rate of one data point/sec and recorded on tape for use by second-generation data analysis programs at a sampling rate of 40 data points/sec. The General Dynamics facility also provides postflight quick-look and engineering-unit data. However, its use as a data reduction facility is normally limited to cases where very rapid data reduction turnaround is required for special problem analysis or to support succeeding flights.

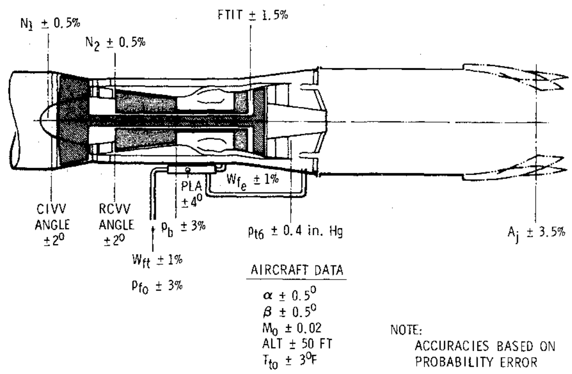

Fig. 5 Propulsion flight test instrumentation.

Data Analysis

All YF-16 data analysis processing is accomplished through the AFFTC Uniform Flight Test Analysis System (UFTAS). The major disciplines involved—which may be viewed as UFTAS subroutines—are aerodynamics, performance, propulsion, structures, and flying qualities. The UFTAS procedure itself provides the necessary controls and overview and the data input/output/transfer functions required to integrate the various subroutines. The particular analysis programs, or subroutines, were developed by General Dynamics as applicable to the YF-16 and supplied to the Air Force for incorporation into UFTAS. The propulsion analysis portion of the program (PROP) was developed to fulfill three primary requirements:

1) Provide computed thrust data from in-flight measurements (and based on YF-16 bookkeeping procedures) which allows derivation of the basic airplane aerodynamic characteristics and performance.

2) Provide the necessary thrust and fuel-flow increments to allow conversion of as-measured airplane performance to standard day and standard Mach/altitude conditions (standardization).

3) Provide sufficient data to analyze engine operating characteristics and monitor engine health.

Programing of PROP permits the program either to be run in conjunction with the aero/performance programs for YF-16/F100 performance analysis or to be run independently of any other programs for F100 operation analysis. In addition, special programing minimizes the necessary control and operating information that must be submitted for each problem, thus keeping the man hours down. The specific manner in which PROP is used is controlled by specifying which of the following computational options is required:

1) Computed inflight thrust (option 1): uses measured inflight data to determine the performance of the YF-16 propulsion system (employs a P&WA in-flight thrust deck for the interim production engine). It also computes corrected gas-generator parameters and prints out various measured temperatures and pressures on the aircraft and the aircraft operating conditions.

2) Predicted engine performance (option 2): uses the P&WA engine status (cycle) deck for the interim production engine to predict engine operating characteristics and performance at the actual test conditions (T_{t_2}, M_0, Alt, PLA).

3) Predicted standard day performance (option 3): uses the engine status deck to generate engine performance at standard day and standard Mach/altitude (or any reference) conditions.

4) Engine analysis (option 4): compares measured engine operating parameters (corrected and uncorrected) with the predicted values and flags conditions that appear anomalous.

5) Stored library data: provides data determined from previous testing (model and subsystem) that are required for generating the installed engine performance (i.e., inlet pressure recovery, nozzle and inlet spillage drag, and engine bleed and shaft power extraction rates).

When all options are exercised a tremendous amount of information is available, with approximately 260 output items listed on two 11- by 17-in. computer sheets for each time frame of data processed. Plotted data in the form of time histories and/or engine parameter cross plots are also available.

The PROP program is proving to be invaluable during the YF-16 program because it provides all the required propulsion system data analysis procedures in one integrated, easy-to-run program that requires a minimal amount of man hours for the total data analysis processing task. At an average of one to two flights per day during the last few months, about two engineering hours are used each day for PROP data processing for propulsion purposes. For support of UFTAS, some additional effort is required to provide propulsion data for the aerodynamic/aircraft performance analysis.

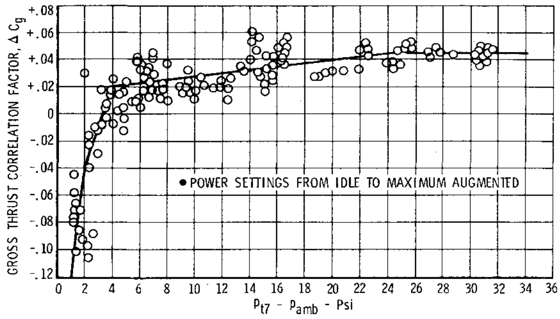

Fig. 6 F100-PW-100 engine gross thrust correlation factor.

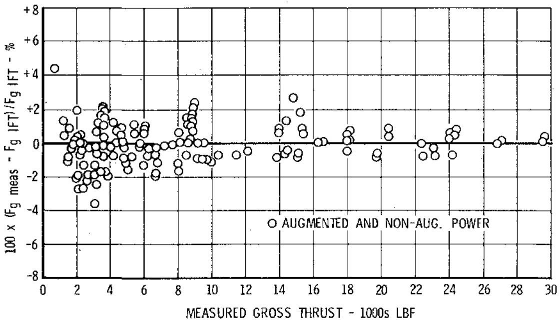

Fig. 7 Gross thrust correlation factor normalizes altitude test data.

In-Flight Thrust Determination Procedure

The method used for determining in-flight thrust on the YF-16 is similar to that used on the F-111/TF30 and other aircraft. Gross thrust is a function of the engine exhaust nozzle pressure ratio, and ram drag is computed using airflow values obtained from the average F100-PW-100 fan map, essentially a calibration of the fan derived from many fan runs on sea level and altitude test stands.

The first step in gross-thrust computation is to determine the ideal gross thrust F_{g_i}, using the nozzle pressure ratio, p_{t_7}/p_0. From the measurement of the mixed turbine/fan discharge total pressure, p_{t_6}, the exhaust nozzle total pressure, p_{t_7}, is computed by subtracting the pressure drop through the afterburner. (The afterburner pressure drop is a calibration from test stand measurements and is a function of the afterburner inlet Mach number and exhaust nozzle area.) The effect of exhaust temperature and composition on the specific heat ratio γ is determined from the fuel/air ratio, based on the fan airflow and measured fuel flow. Thus, the fully expanded ideal gross thrust is computed from the well-known relations

$$F_{gi}=p_{t_7}A_7\left[\frac{2\gamma^2}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\left[1-\left(\frac{p_0}{p_{t_7}}\right)^{\frac{\gamma-1}{\gamma}}\right]\right]^{1/2}$$

for $p_{t7}/p_0>$ critical, and

$$F_{gi}=p_0A_7\left[\frac{2\gamma}{\gamma-1}\right]\left[\left(\frac{p_{t_7}}{p_0}\right)^{\frac{\gamma-1}{\gamma}}-1\right]$$

for $p_{t_7}/p_0\leq$ critical.

However, the ideal gross thrust F_{g_i} must be converted into real gross thrust F_g for the real exhaust nozzle. Initial efforts to do this by use of the primary exhaust nozzle discharge coefficient C_d and the velocity coefficient C_v of the convergent-divergent nozzle were not completely satisfactory in themselves. However, the values of the gross thrust coefficient C_g were correlated with a limited amount of altitude test stand results. An average gross thrust correlation (correction or adder) factor was established from these test stand results. The best correlation was found to exist between the pressure difference across the exhaust nozzle, $p_{t_7}-p_0$ (Fig. 6), and the factor ΔC_g, which is

$$\Delta C_g=(F_{g_{\text{meas}}}-F_{g_i}C_g)/F_{g_i}C_g$$

where

$$C_g=C_vC_d.$$

C_v and C_d came from results of past experience and model tests. The factor ΔC_g is applied to the gross thrust coefficient used in computing the real gross thrust in the in-flight thrust determination procedure. Thus

$$F_g=(1+\Delta C_g)C_gF_{g_i}$$

The result was to normalize the computed gross thrust within about 2% of that measured (Fig. 7).

A word is needed about the net thrust value computed for use with the airplane drag. The thrust/drag bookkeeping system is set up to carry all variations caused by engine power changes on the thrust side of the ledger. Thus, a baseline configuration is established to which all thrust data are corrected. This configuration requires correction of both the inlet spillage drag (additive drag plus lip suction) and the exhaust nozzle external drag. The baseline is a maximum augmented power configuration in terms of the inlet airflow, exhaust nozzle exit diameter, and exhaust nozzle pressure ratio at a constant altitude, standard day. This selected baseline configuration $(A_0/A_i,D_e)$ was used for the YF-16 wind-tunnel force model, thus requiring only small adjustments to the airplane drag data to make them compatible with the net thrust values.

The primary intent of the in-flight thrust procedure is to determine the thrust at the high power settings, that is, intermediate and augmented. The uncertainty introduced by the instrumentation used both on the test stand and in the flight test data package is magnified at low power levels. Thus, data scatter predominates at the lower thrust levels such as those required for cruise on the YF-16. For example, the 2-sigma accuracy of the net thrust levels computed from test stand data

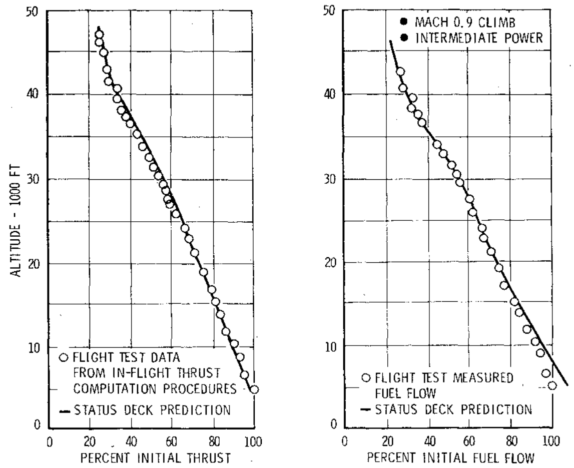

Fig. 8 Intermediate power climb flight test propulsion data.

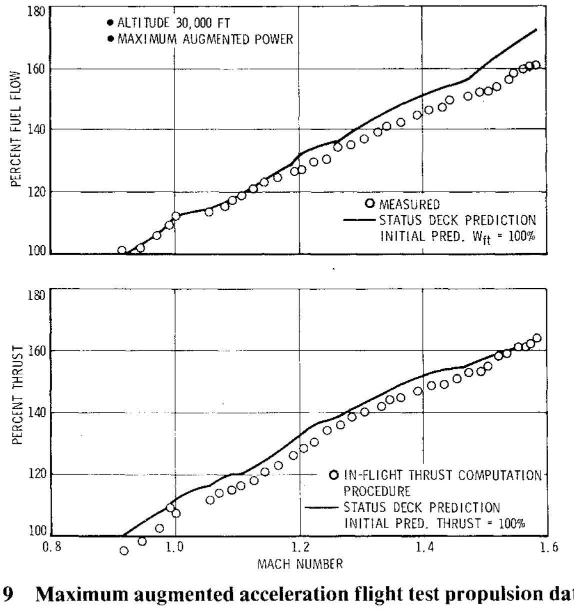

Fig. 9 Maximum augmented acceleration flight test propulsion data.

is ±3.8% at high powers and ±8.3% at subsonic powers below intermediate.

Flight Test Propulsion Performance

The in-flight calculated thrust levels have agreed well with predicted levels from the status deck. Examples of this are seen during both climbs and accelerations in Figs. 8 and 9. Furthermore, the intermediate power fuel-flow levels measured in flight agree with those predicted from the status deck at the higher altitudes but are less than predicted at the lower altitudes. Maximum-power fuel flow appears to have a flatter slope than that predicted.

Standardized test thrust levels are shown in Fig. 10 for maximum augmented power. In comparison to the standard day predicted levels the in-flight values run about 5% low at the higher altitudes. This is suspected to be caused by several factors: 1) engine deterioration, 2) a lag in the ram temperature probe during the rapid acceleration, and 3) a lag in the engine control T_{T_2} sensor. Although a shift in the ram temperature of about 7 or 8°F would bring the test points and predicted lines together, the probability is that all three factors contribute to the 5% lower thrust.

The Air Force Flight Test Center made a key check on the in-flight thrust determination procedure in late June of 1974. YF-16 No. 2 was placed on the AFFTC aircraft test stand, and the engine power setting was varied in increments from idle to

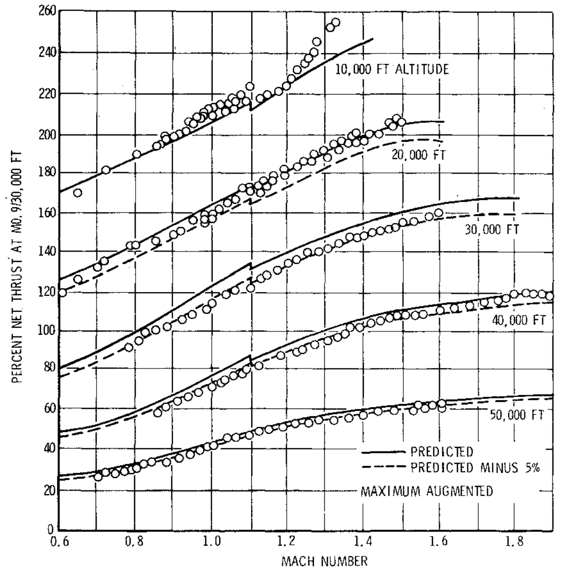

Fig. 10 Comparison of standardized YF-16 flight test thrust with predictions.

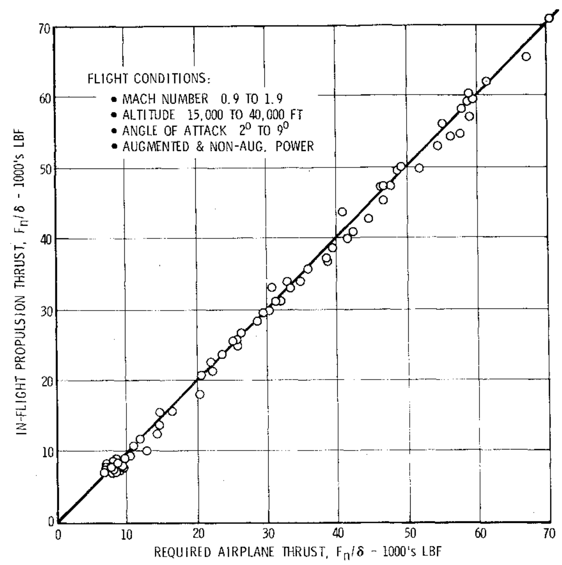

Fig. 11 Comparison of flight test thrusts with required thrust predictions.

maximum augmented and back to idle. Thrust measurements were made by the test stand simultaneously with the recording of engine parameters by the on-board flight test data system. Thrust values were then computed from the recorded engine parameters by the in-flight thrust determination procedure (PROP program) and compared to those indicated by the AFFTC thrust stand. There is very good correlation between the two. The computed thrust slightly exceeded the measured thrust at nonafterburning thrust settings above 50% and fell slightly below for the afterburning thrust values.

An all-encompassing correlation can be made between the in-flight computed thrust and the required thrust level predicted for the aircraft. The predicted thrust required for the YF-16 is based on lift-drag polars established from wind-tunnel tests. It should be noted that the in-flight computed thrusts are adjusted for nonsteady-state flight conditions (aircraft acceleration/deceleration and climb/descent rates). The correlation between the in-flight thrust and the required thrust predicted from the scale models is impressive (Fig. 11). Although one might wish for a little less data scatter for analysis purposes, the agreement is good from the standpoint of the in-flight thrust computation procedure used.

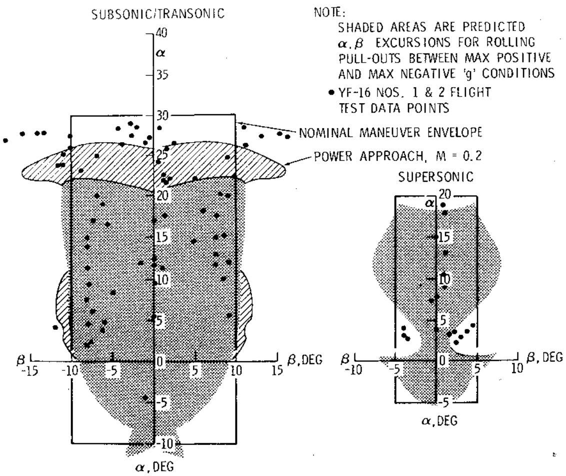

Fig. 12 Inlet/engine compatibility test results.

Propulsion System Operation

Flight Test Results

After nine months of flight testing, the YF-16 had accomplished its scheduled flight test program and had cleared and demonstrated the complete airframe and propulsion system flight envelopes. The YF-16 maneuver envelope and the flight test points at which satisfactory engine operation have been demonstrated are shown in Fig. 12. No propulsion system problems have been encountered during any maneuvering of the aircraft to its limiting conditions, including high-angle-of-attack testing.

Engine power lever transients have been conducted at all extremes of the flight envelope and at aircraft load factors from -1 to $+8.5g$, with very satisfactory operation. A few fan stalls have been encountered, primarily in the upper left-hand portion of the envelope, but are associated with augmentor transients. All stalls encountered were of a self-recovering nature (i.e., the engine surged and immediately returned to intermediate power). The operational flexibility of the propulsion system was demonstrated by several hundred throttle transients of every type throughout the YF-16 flight envelope, including augmentor lights and shutdowns. The pilots used the throttle very freely for whatever purpose they needed to achieve a specified flight situation. For example, there were cases where the augmentor was lit and shut down 25 or more times in a single flight.

Subsonic and supersonic firings of the M-61A gun and AIM-9 missiles have also been accomplished with no impact on propulsion system operation. The YF-16 does not require any engine reset, downtrim, or special control signals during missile or gun firing.

In-Flight Restart Test

In-flight restart tests were successfully accomplished on YF-16 No. 2. The pilot procedure was to establish a desired descent path, initiate the monopropellant emergency power unit prior to engine cutoff to provide uninterrupted hydraulic power, and then place the throttle in cutoff until the desired restart altitude was achieved. The resulting flight paths and restarts were nominally performed as predicted. Just over a minute after the initial movement of the throttle to idle position, the engine regained thrust for level flight, at which time the emergency power unit was turned off.

Conclusions

The following conclusions have been reached:

1) The concept of using a developed engine in a new-aircraft prototype program proved very successful. Most of the birth problems associated with new-engine/new-airframe were avoided because of the extensive experience gained in the F-15 program.

2) P&WA's broad test experience with the F100 engine in the AEDC and FRDC altitude test stands provided a good basis for both the status performance deck and the in-flight thrust calculation procedures, and provided the necessary confidence for predicting and assessing airplane performance.

3) A well-organized propulsion data system and analysis program pays dividends in performance analysis with minimum effort and quick engine diagnostics.

4) The YF-16 and its data system have performed very commendably, and their dependability has resulted in a great deal of flight test data in a short period of time with a minimal flight test budget.

5) Open cooperation between the aircraft and engine manufacturer expedites the design, the data system development, and the solution to problems which surface during the flight test program.