Flight Evaluation of a Digital Electronic Engine Control in an F-15 Airplane

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A digital electronic engine control (DEEC) system on an F100 engine in an F-15 airplane was evaluated in flight. Thirty flights were flown in a four-phase program from June 1981 to February 1983. Significant improvements in the operability and performance of the F100 engine were developed as a result of the flight evaluation: the augmentor envelope was increased by 15,000 ft, the airstart envelope was improved by 75 knots, and the need to trim the engine periodically was eliminated. The hydromechanical backup control performance was evaluated and found to be satisfactory. Two system failures were encountered in the test program; both were detected and accommodated successfully. No transfers to the backup control system were required, and no automatic transfers occurred. As a result of the successful DEEC flight evaluation, the DEEC system has entered the full-scale development phase.

Nomenclature

AJ	= jet primary nozzle area
BUC	= backup control
CENC	= convergent exhaust nozzle control
CIVV	= compressor inlet variable vane
DEEC	= digital electronic engine control
EPR	= engine pressure ratio, PT6M/PT2
FA-AB	= afterburner fuel-air ratio
FTIT	= fan turbine inlet temperature
HIDEC	= highly integrated digital electronic control
HP	= pressure altitude
L/D	= lift-to-drag ratio
LOD	= light-off detector
M	= Mach number
N1	= fan rotor speed
N2	= core rotor speed (100% N2 = 14,000 rpm)
PAB	= augmentor static pressure
PB	= burner pressure
PCM	= pulse code modulation
PLA	= power lever angle
PLA-AB	= afterburner power lever angle
PS2	= fan inlet static pressure
PT2	= fan inlet total pressure
PT6M	= turbine discharge total pressure (mixed core and fan stream)
RCVV	= rear compressor variable vane
TT2	= fan inlet total temperature
VC	= calibrated airspeed
WAC2	= corrected fan airflow
WF	= fuel flow
WFGG	= gas generator fuel flow

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Introduction

THE many benefits of full-authority digital engine control have been repeatedly demonstrated in simulation studies, ground engine tests, engine altitude tests, and flight tests. These benefits include improvements in engine efficiency, performance, operability, and capability of detecting and accommodating failures in real time and providing engine-health diagnostics. As these control systems evolve, there is a continuing need for flight-test evaluation.

The full-authority DEEC was developed for the Pratt and Whitney F100-PW-100 turbofan engine and has been flight-tested in an F-15 airplane at Dryden Flight Research Facility of NASA Ames Research Center. Before flight, DEEC test engines had been tested at the U.S. Air Force Arnold Engineering and Development Center[1] and at NASA Lewis Research Center. The flight evaluation was conducted in four phases. In phase 1, DEEC performance was evaluated over the middle portion of the F-15 flight envelope, and very few problems were encountered.[2] During phase 2, the low-speed, high-altitude portion of the flight envelope was investigated; the augmentor throttle transient limits and the airstart envelope were determined, and the backup control (BUC) system was evaluated.[3] Numerous augmentor blowouts and stalls occurred in defining the limits, and a nozzle instability was encountered. Some of the flight results were not consistent with predictions based on engine simulations and altitude facility tests. As a result of the phase 2 evaluation and ongoing development of the DEEC system, engine tests were conducted at the NASA Lewis Research Center, and a series of engine and control system modifications were developed and flown in the phase 3 flight evaluation.[4] In phase 4, additional logic changes and hardware additions and changes were made. This paper presents the phase 4 flight results and summarizes the results of the DEEC program.

F-15 Airplane

The F-15 airplane (Fig. 1) is a high-performance, twin-engine fighter, capable of speeds to Mach 2.5. The engine inlets are the two-dimensional external compression type with three ramps, and feature variable capture area.

The F-15 is powered by two Pratt and Whitney F100-PW-100 engines (Fig. 2); these are low-bypass-ratio (0.8), twin-spool, afterburning turbofans. The three-stage fan in the F100 is driven by a two-stage, low-pressure turbine. The engine is equipped with a proximate splitter, a fan-core flow divider that extends forward to the trailing edge of the fan blades.

The ten-stage, high-pressure compressor is driven by a two-stage high-pressure turbine. The engine incorporates CIVV and RCVV to achieve high performance over a wide range of power settings; a compressor bleed is used only for starting. Continuously variable thrust augmentation is provided by a mixed-flow augmentor that is exhausted through a convergent-divergent nozzle having a variable diameter. The augmentor incorporates five spray-ring segments, which are initiated sequentially. Segments 1, 2, and 4 are located in the core stream, and segments 3 and 5 are located in the fan duct stream. The augmentor was equipped with dual augmentor ignitors, whereas the standard F100 engine has only one. For phase 4, the engine was equipped with a production flameholder; a ducted core flameholder was used in the earlier phases.[3] The engine was also equipped with a hemispherical head static pressure probe (PS2) that is not on the standard F100 engine; the probe was located on the engine hub.

The F100 engine used for the DEEC evaluation was serial No. 680063. It had been rebuilt from an earlier F100(2) engine to a zero-time F100(3) configuration with the DEEC system before the DEEC flights. The engine had accumulated 9.8 h of sea-level testing and 45.4 h at an altitude facility before the first DEEC flights.

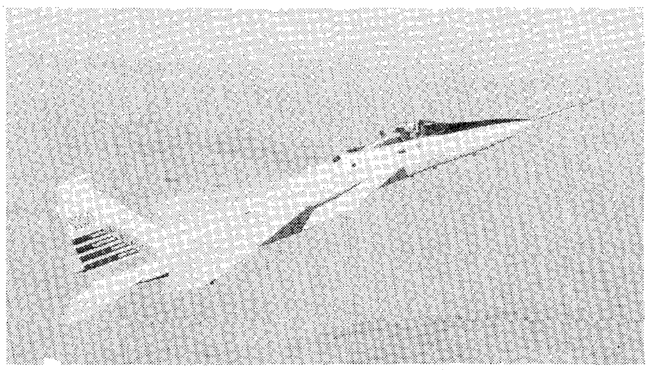

Fig. 1 F-15 airplane used for DEEC flight evaluation.

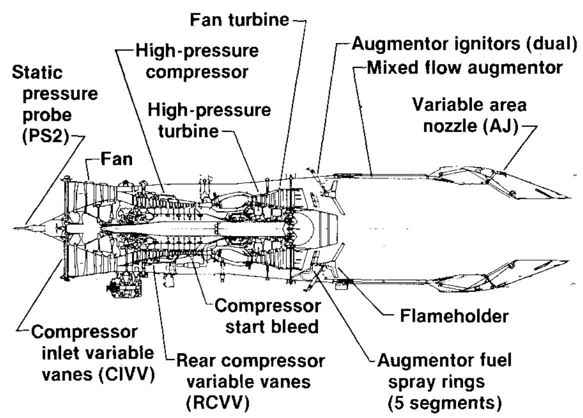

Fig. 2 Sectional view of F100 engine used in DEEC flight evaluation.

DEEC Description

The DEEC is a full-authority, engine-mounted, fuel-cooled digital electronic control system that performs the functions of the standard F100 engine hydromechanical unified fuel control and of the supervisory digital engine electronic control. The DEEC consists of a single-channel digital controller with selective input-output redundancy, and a simple hydromechanical BUC. The system is functionally illustrated in Fig. 3. It receives inputs from the airframe through power lever angle (PLA) and Mach number M, and from the engine through pressure sensors, PS2, PB, and PT6M, temperature sensors TT2 and FTIT, rotor speed sensors N1 and N2, and the light-off detector (LOD) of the ultraviolet flame sensor. It also receives feedbacks from the controlled variables through position feedback transducers indicating variable vane (CIVV and RCVV) positions, metering valve positions for gas-generator fuel flow (WFGG), augmentor core and duct fuel flow, segment-sequence valve position, and exhaust-nozzle position (AJ). Dual sensors and position transducers are used (Fig. 3) to achieve redundancy in key parameters.

The input information is processed by the DEEC computer to schedule the variable vanes (CIVV and RCVV), to position the compressor start bleeds, to control gas-generator and augmentor fuel flows, to position the augmentor segment-sequence valve, and to control the exhaust-nozzle area. Redundant coils are present in the torque motor drivers for all of the actuators.

DEEC Logic

The DEEC logic provides open-loop scheduling of CIVV, RCVV, start bleed position, and augmentor controls. The DEEC incorporates closed-loop control logic for airflow and engine pressure ratio (EPR) by controlling WFGG and AJ. With this closed-loop logic, it is possible to eliminate the need

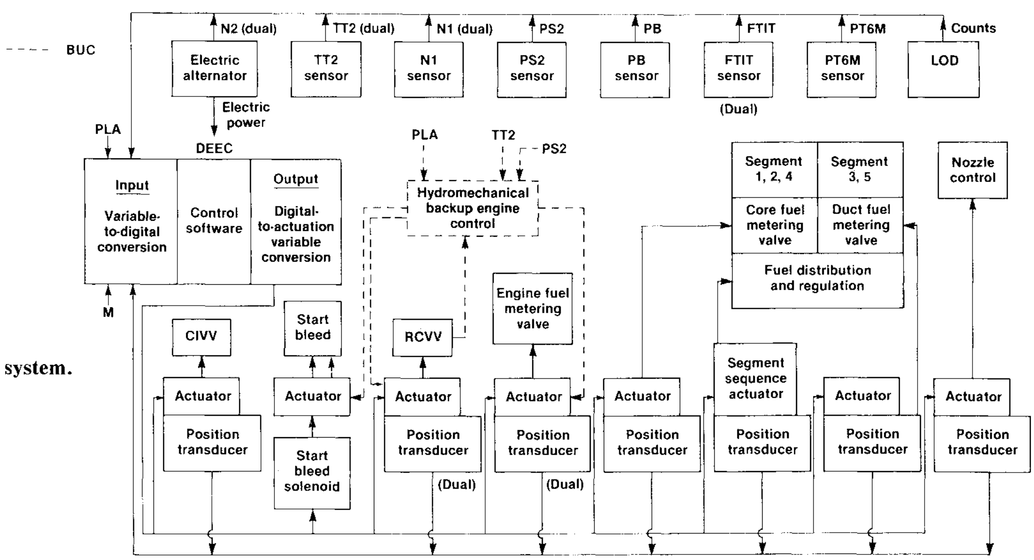

Fig. 3 Block diagram of DEEC system.

for periodic trimming and to maintain performance. The two main closed loops are shown in Fig. 4. The top portion of the figure shows the total airflow logic in which WFGG is modulated to maintain the scheduled fan speed and, hence, airflow. Proportional-plus-integral control is used to match the N1 request to the sensed N1. Limits of N2, FTIT, and PB are maintained. The airflow loop is used for all throttle settings.

The engine pressure ratio (EPR) loop is shown in the lower portion of Fig. 4. The requested EPR is compared with the EPR, based on PT2 and PT6M. Using proportional-plus-integral control, the nozzle is modulated to achieve the requested EPR. The EPR control loop is only active for intermediate power operation and augmentation. At lower power settings, a scheduled nozzle area is used.

With the closed-loop airflow and EPR logic, the DEEC control is capable of automatically compensating for engine degradation. Engine pressure ratio is directly related to thrust; hence, the DEEC can maintain an engine at a desired thrust level. As the engine degrades, the FTIT required to achieve the scheduled EPR will increase until it reaches its limit. The DEEC cannot maintain desired thrust when the engine is on the FTIT limit.

The PT2 signal is derived from the PS2 measurement and engine airflow. A PT2-PS2 relationship was determined from previous wind tunnel and flight tests.[5]

Augmentor Logic

Augmentor fuel distribution is handled by a segment-sequencing valve (Fig. 3). Each of the five segments has a hydromechanical "quick-fill" feature, which supplies a high fuel-flow rate to fill the fuel manifold and spray ring. A mechanical quick-fill sensor determines when each segment is full by the rise in fuel pressure, turns off the quick-fill fuel flow to that segment, and transfers that segment to the metered fuel flow scheduled by the DEEC computer. The segment-sequencing valve handles the sequencing of quick-fill and distribution of metered flow, and the separate core and duct fuel-flow metering valves control the flow to the segments.

The DEEC incorporates a maximum segment 1 limiting feature in the upper left-hand corner of the flight envelope. This limits the augmentor to the maximum segment 1 fuel flow, even when a higher power setting has been requested. In addition, an override switch was installed in the cockpit for this flight evaluation; this switch made it possible to override the maximum segment 1 limit and achieve full augmentation.

For the phase 4 DEEC flight evaluation, an LOD was installed. This ultraviolet sensor had an output proportional to flame intensity (LOD counts). With the LOD, additional logic was incorporated to detect automatically augmentor blowouts and to attempt relights without pilot action. Once a blowout was detected, the DEEC logic turned off the augmentor fuel, performed an LOD self-check, and then reinitiated the augmentor sequence (termed a PLA recycle). The LOD was also used after the segment 1 light was detected. A certain minimum flame strength (in terms of LOD counts) was required before the sequence would proceed to the additional segments. Up to three PLA recycles were allowed without pilot action.

The LOD was also used for the "fast-thrust-response" logic feature. For throttle transients from idle to maximum power, the augmentor sequencing could be initiated while the speeds of the rotors were increasing, thus permitting a more rapid increase in thrust. At high levels of PT2 (10 lb/in.^{2}), segment 1 could be turned on at idle conditions. The LOD signal was used to verify the light and to permit the subsequent segments to be turned on. At lower levels of PT2, augmentor initiation was delayed to higher values of fan speed, and in the upper left-hand corner, 98% of the scheduled fan speed was required before operation was initiated.

Airstart Logic

The DEEC incorporates closed-loop logic for airstarts. A scheduled value of high-rotor-speed acceleration is compared with the actual value and the gas generator fuel flow is modulated to maintain the scheduled value. This closed-loop feature reduces the possibility of hot starts or hung starts and permits successful airstarts at lower airspeeds. Details of the airstart logic and results are given in Ref. 6.

Backup Control

The BUC in the DEEC system is a simple hydromechanical engine control housed in the same unit as the DEEC gas-generator fuel-metering valves. BUC is limited to non-augmented power and is operable, at a reduced performance level, over the entire engine operating envelope. Additional information on the DEEC and BUC is given in Refs. 3 and 4.

Data Acquisition and Reduction

Pressures, temperatures, rotor speeds, fuel flows, and positions were measured by independent instrumentation on the DEEC test engine. In addition, a serial digital data stream from the DEEC computer was recorded. In phase 4, the serial data stream contained 83 words. Angles of attack and sideslip, nose-boom total and static pressure, and other aircraft parameters were measured. Data were recorded on a pulse-code-modulation (PCM) system. High-frequency response parameters, such as PB, PAB, PT2, and the augmentor segment fuel pressures, were recorded at 200 samples/s. The data were recorded on a tape recorder aboard the F-15 airplane and

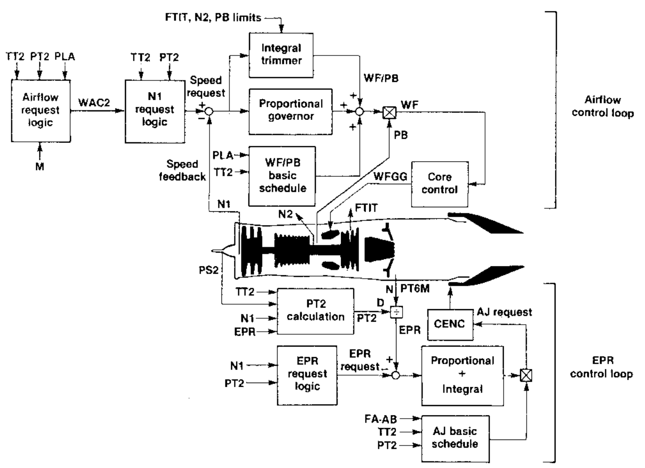

Fig. 4 DEEC basic control modes.

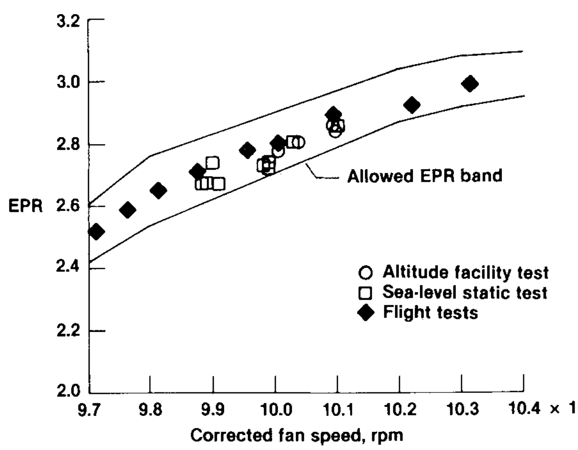

Fig. 5 Test results for DEEC no-trim feature.

also were telemetered to the ground for recording and for real-time analysis and display.

Tests and Procedures

The DEEC flight evaluation consisted of 30 flights, including 5 flights during phase 4; the total flight time was 35.5 h. The evaluation comprised 994 augmentor transients, 155 airstarts, more than 280 nonaugmented transients, BUC evaluations, maneuvering flights, accelerations, and climbs. A maximum Mach number of 2.36 was reached, and a minimum airspeed of 99 knots at an altitude of 25,000 ft was achieved. Climbs were made to 60,000 ft to evaluate the upper limits of augmentor operation.

For other points in which stabilized speed and altitude were required, the pilot used the right engine to control speed while the left engine was evaluated. In maneuvering flight, large angles of attack and sideslip (up to about 25 and 15 deg, respectively) were flown, and throttle transients were performed. Test procedures are described in Ref. 2.

There were two basic types of throttle transients: throttle snaps and throttle bodies. A throttle snap is a rapid single-direction movement from one stabilized power setting to another. A bodie begins with a snap in one direction, followed closely by a snap in the other direction before stabilization.

For augmented transients, a series consisted of a throttle sequence from intermediate to maximum to intermediate, followed by snap sequences from idle to maximum to idle. No attempt was made to allow the augmentor manifolds to drain completely between transients. When stalls or blowouts occurred at a given test point, the transient was repeated until the same result was achieved in two of three trials. Augmentor transients performed in the upper left-hand corner of the flight envelope were limited by the DEEC logic to maximum segment 1; however, with the override switch in the cockpit, full augmentation could be achieved.

For airstarts, the pilot set up at the desired test condition, advanced the throttle to intermediate power to provide repeatable initial conditions, and then shut down the engine. As the engine spooled down to the desired N2 speed, the pilot moved the throttle to idle to initiate the airstart. Speed and altitude were maintained using the right engine until the test engine reached idle rpm, or until an unsuccessful airstart was evident. Unsuccessful airstarts were indicated either by increasing FTIT with decreasing N2 (hot start), or by a very slow or zero rate of increase in N2 (hung start). All airstarts were performed with the normal F-15 bleed and accessory loads.

Results and Discussion

DEEC No Trim

The closed-loop logic in the DEEC (Fig. 4) eliminates the need to trim the engine periodically to keep it within operating limits. The results over the four phases of the DEEC program are summarized in Fig. 5. The engine pressure ratio data as a function of corrected airflow are shown for altitude tests, sea-level tests, and for the four flight phases. As shown in Fig. 5, the results fall well within the allowable EPR band. The potential benefits of the no-trim feature are quite significant. Installation of the DEEC system on one-half of the F-16 fleet would produce savings of $150 million over the lifetime of the fleet. This is a combination of savings resulting from the fuel and labor saved by not requiring trim, and the engine hours that would not be expended in the trimming operation.

Airstarts

The closed-loop airstart logic of the DEEC was evaluated in a large number of spooldown airstarts; the results are summarized in Fig. 6. Spooldown airstarts were made at 40 and 25% N2. At altitudes between 10,000 and 35,000 ft, all airstarts at airspeeds of 200 knots and above were successful. The success line shown in Fig. 6 indicates an improvement of about 75 knots over the standard F100 limit designated in the engine handbook. Airstarts utilizing the F-15 jet-fuel starter were also evaluated; all were successful, even at speeds as low as 150 knots. This is a significant capability because it allows airstarts to be attempted at the maximum L/D speed of the F-16 airplane. The airstart results are presented in more detail in Ref. 6.

Fault Detection and Accommodation

No faults occurred during the phase 4 DEEC evaluation. For the entire 30-flight program there were two faults. Both were sensor failures, and both were successfully detected and accommodated. No automatic transfers to the BUC were required, and none occurred.

Nonaugmented Throttle Transients

During the DEEC evaluation, over 280 nonaugmented throttle transient tests were conducted, and all were successful. Throttle snaps and bodies were made at the boundaries of the envelope and during maneuvers, and no problems were encountered.

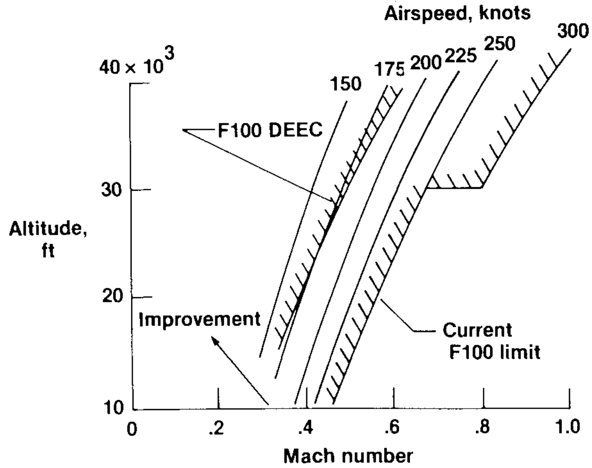

Fig. 6 Results of DEEC airstart tests.

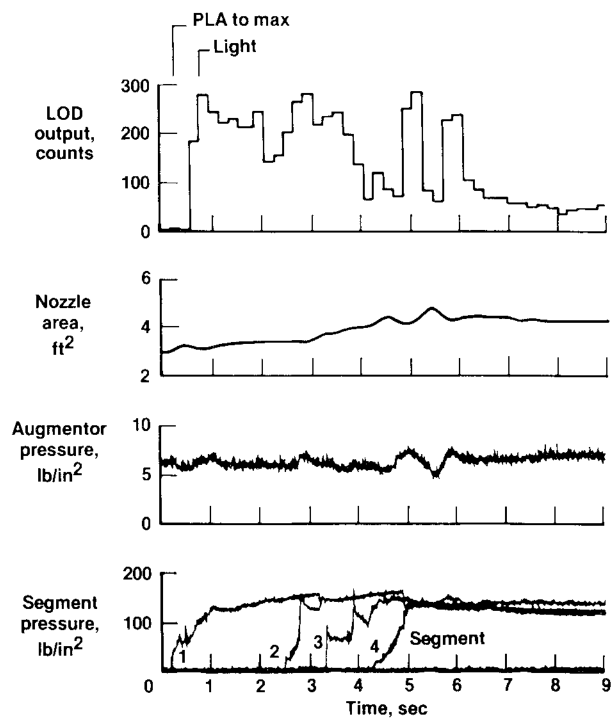

Fig. 7 Example of throttle transient from military to maximum power: HP = 45,000 ft, VC = 125 knots.

Augmented Throttle Transients

The largest part of the DEEC flight evaluation involved the investigation of the augmentor transient capability. There have been occasional stalls and blowouts in the standard F100 engine during throttle transients, and a goal of the DEEC program was to minimize these problems. By the end of the DEEC phase 2 flight evaluation, there had been numerous stalls and blowouts.[3] In the phase 3 evaluation, modifications were evaluated, and significant improvements were demonstrated.[4] The primary goal of phase 4 was to evaluate the augmentor transient performance with the LOD and additional improvements to the logic.

Augmentor transients were first made without the cockpit override switch. The DEEC logic limited the upper left-hand corner (of the flight envelope) transients to maximum segment 1. With the segment 1 limit in effect, there were no stalls or blowouts, and the PLA recycle logic was never needed. In order to evaluate the augmentor capability fully, the override switch was used to allow full augmentor capability. All the data given in this paper were acquired with the switch in the override position.

An example of the performance of the LOD is shown in Fig. 7, a snap transient from military to maximum power at an altitude of 45,000 ft and an airspeed of 125 knots. As shown in Fig. 7, the segment 1 fuel flow began when the throttle reached maximum power, and the LOD indicated a light almost immediately. The logic held the sequencing for 1.25 s and then turned on segments 2, 3, and 4. The nozzle opened to maintain EPR, and the augmentor static pressure PAB showed no sharp changes. A small nozzle oscillation occurred just as segment 4 was turned on, and the LOD showed some fluctuations that are probably a result of movement of the flame pattern. Although transients at this condition were unsuccessful in previous phases, this one was successfully completed.

An example of a snap from idle to maximum power at 50,000 ft and 150 knots is shown in Fig. 8. Following the advance of PLA to maximum, more than 5 s were required for the fan speed to reach 98% of its scheduled value, at which time augmentor-ignition requirements were satisfied. The light was indicated by the LOD shortly after segment 1 was turned on. Following the segment 1 hold, the remaining three segments were turned on, and the transient was successfully completed. The LOD decreased to levels below 100 counts, but no blowout occurred. During previous phases of testing, these transients were not successful. However, augmentor ignition had been permitted at 80% fan speed, and the segment 1 hold was shorter.

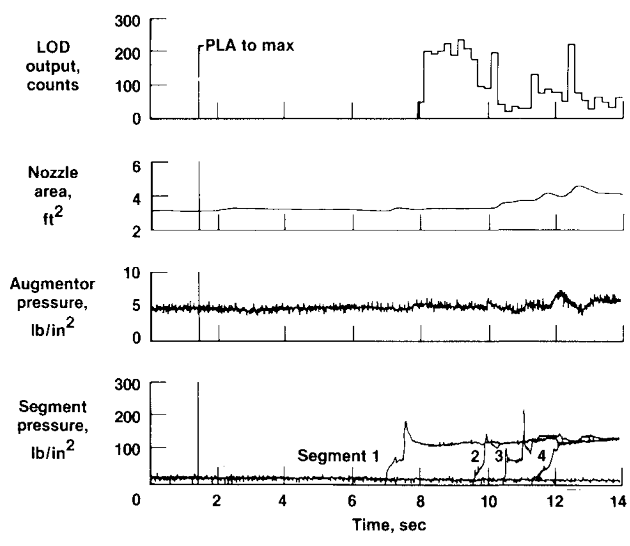

Fig. 8 Example of throttle transient from idle to maximum power: HP = 50,000 ft, VC = 150 knots.

When a blowout did occur, the DEEC logic recycled the PLA automatically, as shown in Fig. 9. Following a snap transient from military to maximum power at 50,000 ft and 175 knots, the LOD indicated a light. However, the LOD decreased during the segment 1 hold, indicating a poor quality flame. Note that LOD counts in segment 1 had been approximately 200 in the two previous examples. Segments 2 and 3 were turned on successfully, but a blowout occurred immediately after segment 4 began. The logic turned off the augmentor fuel flow and performed an LOD self-test. After 1 s, segment 1 fuel flow was again turned on, and a light was indicated immediately. The LOD counts remained high during the segment 1 hold, and the transient was completed successfully.

During the phase 4 flight evaluation, PLA recycles were occasionally required at altitudes of 45,000 ft and above and at airspeeds below 200 knots. No more than two recycles were ever required. Segment 1 light-off was achieved successfully on the first attempt in all cases; no "no-lights" occurred.

Figure 10 summarizes the transients from military to maximum power for phase 4 with the augmentor override switch on. The data indicate that all transients were successful at altitudes up to 50,000 ft. Additional tests were performed at altitudes of about 50,000 ft to try to determine the upper limit of successful operation. One nonrecoverable stall occurred at 52,000 ft at 175 knots, but all other tests were successful. Success boundaries for the standard F100 engine and for the DEEC engine during phases 2 and 3 are also shown in Fig. 10.

A summary of the throttle transients from idle to maximum power, again with the augmentor override switch on, is shown in Fig. 11. All the attempted transients were successful, although some PLA recycles were required. No stalls occurred. The success lines for the standard F100 and the previous DEEC tests are shown in Fig. 11. The DEEC phase 4 results provide full augmentor capability to the edge of the envelope, an improvement of almost 15,000 ft over the standard F100 engine.

Fast-Thrust-Response Tests

The fast-thrust-response throttle transient capability allows augmentor ignitions while engine speed is substantially below

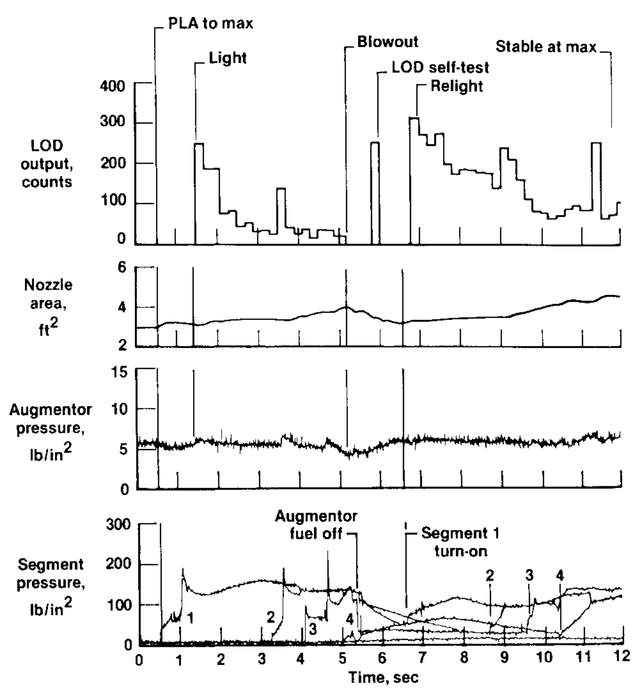

Fig. 9 Example of DEEC PLA recycle logic, throttle transient from military to maximum power: HP = 50,000 ft, VC = 175 knots.

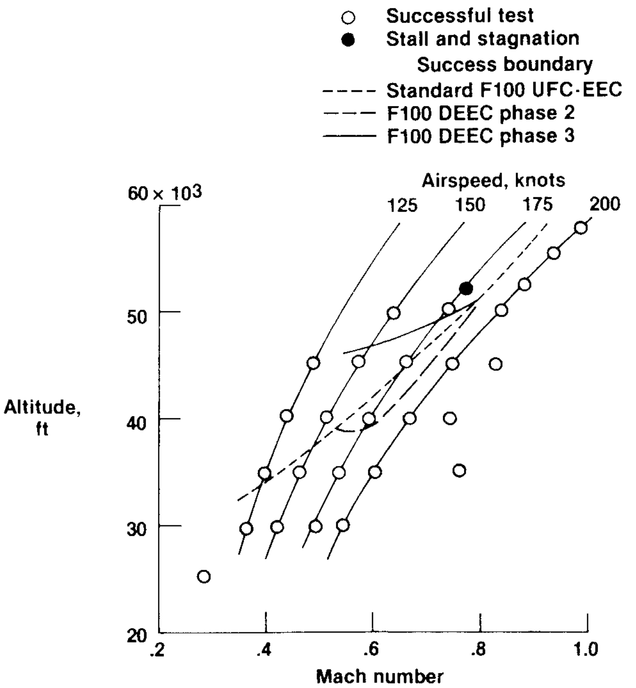

Fig. 10 Summary of transients from military to maximum power.

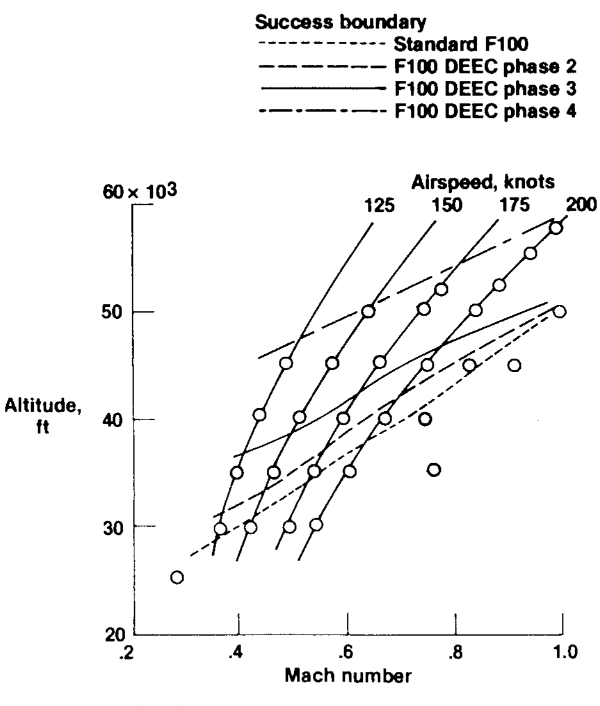

Fig. 11 Test results of throttle transients from idle to military power.

intermediate power. This concept was evaluated by performing snap transients from idle to maximum power at low altitudes. An example at 21,000 ft and 400 knots is shown in Fig. 12. Segment 1 fuel flow was turned on almost immediately while the rotor speeds were accelerating. The LOD detected a light at 1 s. Only a small perturbation was seen in PAB. Segment 2 also was turned on before intermediate power rotor speeds were achieved. Maximum power was reached in 4.3 s. Without the fast-thrust-response logic, however, the augmentor lighting sequence would have been initiated after intermediate power was achieved, and this same transient would have taken almost 7 s. The fast-thrust-response logic, evaluated at several conditions, operated successfully in all instances.

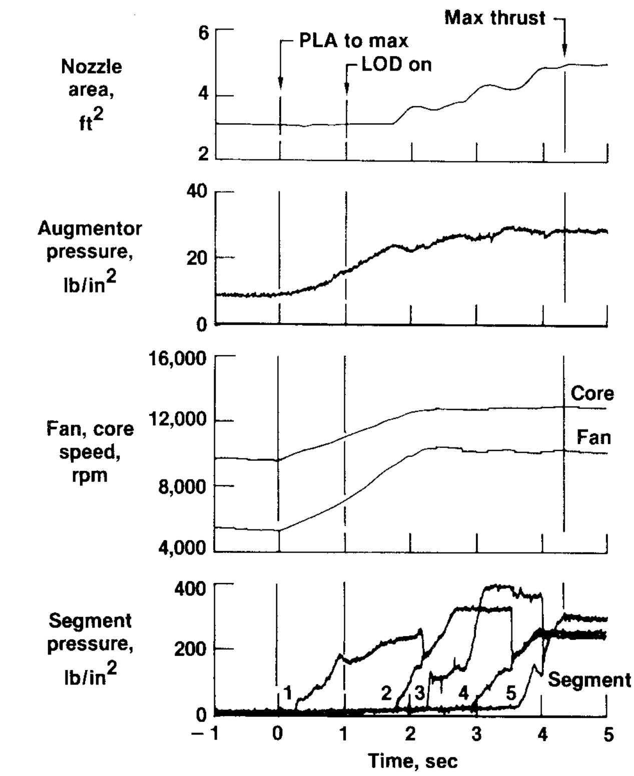

Fig. 12 Example of DEEC fast-thrust response logic: HP = 21,000 ft, VC = 400 knots.

Future Plans

The U.S. Air Force has decided to proceed with full-scale development of the DEEC, based at least partially on the successful flight demonstration in the F-15 airplane.[7] The DEEC system has been tested in an F-16 airplane, and those tests will continue.

The DEEC, with its digital interface capability, provides an opportunity to integrate the engine-control function with other systems on an airplane. A NASA program designated HIDEC (highly integrated digital electronic control) is being formulated to integrate the engine with the flight-control system on an F-15 airplane.

Concluding Remarks

A four-phase flight evaluation of a DEEC system was conducted on an F100 engine in an F-15 airplane. The DEEC system provided major improvements in performance and operability over the standard F100 engine. The no-trim feature of the DEEC was validated; this feature could result in savings of $150 million if one-half of the F-16 fleet were equipped with DEEC systems.

The airstart envelope was investigated, and the DEEC was found to result in an improvement of about 75 knots in the airstart envelope. All DEEC airstarts above 175 knots were successful, and all airstarts assisted by the jet fuel starter were successful, including those at speeds of 150 knots. Over 280 nonaugmented throttle transients were attempted, including snap transients and bodies; all were successful.

There were two failures of the DEEC system during the flight evaluation; both were sensor failures, and both were successfully detected and accommodated. No automatic transfers to the BUC system were required, and none occurred.

The augmentor transient performance was evaluated in almost 1000 tests. At the end of the phase 4 tests, all throttle snaps from idle to maximum power were successful. This represented an altitude improvement of almost 15,000 ft over the standard F100 engine. The fast-acceleration logic permitted idle-to-maximum transients to be completed in 4.3 s at low altitudes.

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