DIGITAL CONTROL BRINGS LARGE TURBOFAN BENEFITS TO THE REGIONAL JETLINER TURBOFAN MARKET

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ABSTRACT

In keeping with the general industry trend of applying Full Authority Digital Electronic Control (FADEC) technology to small gas turbine engines, Textron Lycoming and Chandler Evans Division of Coltec Industries have developed and qualified a single channel control system for use on the Textron Lycoming LF507-1F turbofan engine. The LF507-1F is the world's smallest FADEC-equipped airline turbofan engine and is the only FADEC-equipped turbofan developed and certified for the regional jetliner market. The application for this powerplant, the four-engine AVRO International Aerospace RJ Avroliner series of aircraft, began airline service in April of 1993.

The FADEC employs modern control algorithms to achieve surge-free operation over the flight envelope while providing rapid transient performance and crisp handling qualities. The control interfaces with the aircraft via an ARINC 429 data link to control each engine automatically to the desired power setting with or without N1 synchronization. A simple hydromechanical backup control provides full dispatch capability in the event of a critical FADEC system failure. In addition, the FADEC includes advanced diagnostics for fault identification to the line replaceable unit (LRU) level without specialized test equipment.

This paper describes the architecture, primary features, and development process of the engine control system. Emphasis is placed on the design characteristics and technical challenges unique to the development of an inexpensive control system for the low thrust turbofan market.

INTRODUCTION

Regional airlines are increasingly demanding large aircraft performance, operability, and maintainability at small aircraft prices. One way to provide features such as autoland capability and advanced diagnostics is to equip regional jetliner engines with FADEC control systems. However, FADEC system development for the regional jetliner market poses a unique combination of challenges: developing advanced control systems for small, low cost commercial gas turbines, and meeting the specific needs of regional airlines. As the smallest FADEC-equipped airline turbofan in the world and the only regional jet turbofan engine with a FADEC system, the LF507-1F faced both challenges.
The lower purchase price of smaller powerplants places tight limits on the cost of the control system and the cost of the development effort. Each dollar of control system cost or amortized development cost has a much larger impact on engine and aircraft price than in the large aircraft/large turbofan market. It is for this reason that most smaller commercial turbofan, turboprop, and rotary wing applications use simple hydromechanical or pneumatic controls.

Regional aircraft typically fly eight or more short flights a day and are operated by smaller airlines with limited ability to replace a grounded plane. Maintaining aircraft dispatch capability via fault tolerant systems is essential for airline profitability. Even brief maintenance-related delays, tolerable on longer flights, result in canceled flights and lost revenues for regional airlines due to the short flight length and heavy aircraft utilization. Quick diagnosis of malfunctions and identification of the failed component without expensive ground equipment or troubleshooting procedures is critical to these smaller airlines, which often have limited maintenance facilities compared to the major airlines.

BACKGROUND

The LF507-1F is a 7000 lb thrust high-bypass geared turbofan specifically designed for the short-cycle regional market. The two-spool engine incorporates a supercharger, axial and centrifugal compressors, a reverse flow annular combustor, a two-stage gas generator turbine, a two-stage power turbine, and a FADEC control system. The engine is shown in Figure 2.

The FADEC system is based on a single channel FADEC platform developed on an Independent Research and Development (IRAD) program in the mid-1980s. Although the components on which the FADEC Electronic Control Unit (ECU) is based are no longer the latest state-of-the-art, this inexpensive hardware has proved reliable in applications in many industries. The IRAD ECU design required only a few simple, low-risk modifications to meet the LF507 control needs and the latest regulatory requirements. The same applied to the hydromechanical metering unit (HMU), also developed under the IRAD program and 85% common with an HMU already in production on a Lycoming military turboshift engine.

Choosing a proven, low risk ECU/HMU hardware platform allowed resources to be focused on developing software to provide the desired control, maintenance, and airframe interface features. Selecting a single channel architecture with a hydromechanical backup "manual mode" provided a low-cost system with dispatch reliability similar to that of dual channel systems. Inclusion of the manual mode also addressed the apprehension expressed by several potential customers regarding the total dependance on electronics of systems without a mechanical backup control mode.

HARDWARE OVERVIEW

The main components of the engine control system, as shown in Figure 3, consist of an engine-mounted ECU, an HMU, inlet (T1) and exhaust gas (EGT) temperature probes and a fan speed (N1) sensor. The flush-mounted T1 probe requires no de-icing, reducing cost and complexity compared to systems with aspirated or heated immersion probes. Also included is a maintenance soft fault indicator and a fan speed trim resistor. The ECU contains transducers for measuring ambient pressure (P1) and compressor discharge pressure (P3).

Electro-mechanical devices within the HMU include a core speed (N2) pickup, a three-phase alternator with voltage regulator and redundant N2 speed winding, a stepper motor for positioning the fuel metering valve, and a solenoid for controlling interstage bleed. A two-position interstage bleed control strategy was selected to reduce HMU cost and complexity compared to a continuously variable bleed control. The HMU also contains sensors for measuring HMU power lever angle (PLA) and fuel metering valve position plus a solenoid for transitioning between the electronic and hydromechanical control modes (Auto and Manual). The HMU power lever is mechanically linked to the cockpit throttle.

The ECU is built around the workhorse eight-bit Intel 8085-2 microprocessor. This inexpensive processor requires less supporting electronics than newer 16-bit or 32-bit processors, further reducing cost and complexity and increasing reliability. The microprocessor operates at a 5 MHz rate with a cycle time of 48 milliseconds, which provides adequate time for computations while maintaining acceptable control stability and bandwidth. Critical signals are sampled once per cycle with all analog signals being multiplexed through a ten-bit digital-to-analog converter; speed signals pass through phase-locked loop frequency multipliers, the outputs of which...
are then digitized via counter/timers. The ECU also includes one ARINC 429 transmitter and two receivers to communicate with the aircraft digital flight guidance computers (DFGC) and flight data recorder (FDR).

As shown in Figure 4, the ECU includes an LED hexadecimal fault display with decoding decal. When these codes are used with the straightforward maintenance manual troubleshooting procedures, the failed line replaceable unit (LRU) can quickly and accurately be identified right at the engine and without special test equipment.

**SYSTEM OVERVIEW - AUTO MODE**

The primary control mode during Auto mode operation consists of an isochronous outer loop fan speed governor operating through a P1-biased inner loop N2 rate controller, or NDOT governor. Demanded N1 speed is set as a function of throttle position, with a limited authority trimming function allowing control to an N1 speed request received from the flight guidance system on the ARINC 429 data bus. This feature reduces pilot workload when setting thrust and enables speed synchronization between engines to reduce acoustical noise. An anticipator function is included to eliminate the momentary N1 disturbance that would otherwise be produced by the opening and closing of the two-position interstage bleed on slow transients.

The NDOT governor makes use of a simple inverse engine model state estimator with an integrator and a variable gain to null out the error. Figure 5 illustrates the performance of both the NDOT and N1 governors during a large scale accelerations at 15,000 feet. Testing and simulation of the NDOT governor over a wide range of load and bleed conditions has demonstrated its ability to provide consistent, repeatable transient performance.
The ECU calculates a synthesized, or biased, EGT signal (EGTB) as a function of engine pressure ratio and exhaust gas temperature. This signal is transmitted to the airframe for cockpit display and is used by the control as the temperature feedback parameter. N1, N2, and EGTB topping governors are provided along with a variable N2 floor function. This bottoming governor uses information received from the air data and flight guidance computers to calculate a minimum N2 speed, ensuring that a sufficient level of bleed air is available for cabin pressurization and anti-icing over the flight envelope.

**SYSTEM FUNCTION - DISPATCHABLE MANUAL MODE**

Fuel ratio units (WF/P3) are scheduled strictly against throttle position (PLA) at and above idle in manual mode. Ground and inflight start capability is provided by scheduling fuel flow open loop as a function of PLA position below idle. The two-position compressor interstage bleed is scheduled against N2 speed. This system provides full thrust modulation capability from start to maximum thrust over the entire flight envelope.

Manual mode can be pilot selected or is automatically enabled upon failure of a critical FADEC system component or loss of both primary and secondary electrical power sources. If manual mode is enabled at PLA levels corresponding to takeoff or climb thrust levels, the system reverts to a "fail fixed" mode to ensure flight safety. Fuel flow and thrust remain constant at the pre-failure levels until the PLA is retarded to a low thrust position, at which time manual mode is fully engaged. If manual mode is selected at lower PLA levels, manual mode is immediately engaged to provide instant thrust modulation capability.

This simple PLA-based open loop control strategy requires the use of powerplant anti-ice bleed and the normal cabin pressurization bleed to ensure adequate surge margin over the entire flight envelope. This allows the LF507-1F to provide a dispatchable backup system at a much lower cost than typical hydromechanical controls that vary WF/P3 acceleration schedules with N2/\sqrt{\theta} and provide closed loop speed governing.

**THE DEVELOPMENT PROCESS**

Selecting a proven ECU/HMU hardware platform allowed resources to be focused on developing the software for the desired capabilities. Several strategies were used to reduce cost and development time by identifying control law and logic errors in the design phase, before coding of software.

Previous work had identified that the vast majority of design problems with diagnostic and other finite state logic were caused by interdependent logic that was not properly linked. A simple example better illustrates this:

Consider diagnostic logic that deems a fan speed sensor to be failed when fan speed is 0.0% with core speed at or above idle. Consider also logic that sets core speed to the current sensed value if the core speed sensors are healthy and sets core speed to the "last healthy value" after both core speed sensors have failed. Should the core speed sensors fail above idle, core speed will be set to the last good (above idle) measurement, and a fan speed sensor failure will be erroneously detected at engine shutdown. The fan speed sensor failure detection logic must consider the health of the core speed sensor as well as core speed.

The proper linking of complex logic, although simple in principle, is a difficult task. A process known at Lycoming as an Interdependent Logic Review was conducted on all diagnostics and airframe/flight guidance system interface logic in the design phase. The review process is also conducted on all proposed software changes. Approximately 64% of all known improperly linked interdependencies were identified via this process, as opposed to past experience where most were found at bench, engine, or flight test. In fact, only two interdependencies were found at flight test over a two year period.

A non-real time simulation using a full control model married to a high fidelity aero-thermodynamic engine model was used for control law and schedule design. Control laws and schedules were designed with much more confidence that the resulting engine performance would meet requirements than if aero-thermal models alone (without a control model) or linear engine models were used. Flight tests became confirmatory in nature, with only minor control law or schedule fine tuning necessary.

A real time simulation facility at Chandler-Evans was used for closed loop testing of each software version prior to engine test. The facility mated an actual FADEC to a linearized partial-derivative real-time engine model, with capability for both wet and dry bench configurations. The wet bench...
configuration included an HMU in the loop to evaluate overall systems integration, while the "dry" bench consisted of engine and HMU simulations for software verification and validation.

Extensive use of the Interdependent Logic Review and the non-real time and the real time simulations significantly reduced program cost and risk and accelerated the development process. Many problems were identified and resolved in the design phase or the laboratory instead of during more costly engine or flight testing. In addition, the system design was validated over many more potential flight conditions and engine variations than could have been accomplished using only engine and flight testing.

UNIQUE DEVELOPMENT CHALLENGES

FADEC function can be classified into one of three categories; engine control, airframe interface, and FADEC system diagnostics. Aircraft/flight guidance system interface development was uneventful, due in large part to the Interdependent Logic Review, and is therefore not discussed herein. Control law and schedule design is typical of modern FADEC systems. With three exceptions, control law/schedule development was also uneventful and therefore not discussed herein. Those three exceptions and development of the diagnostics features and maintenance approaches to suit the needs of the regional jetliner market are discussed below.

Fuel Manifold Effects:
Early development flight testing uncovered sustained oscillations during low power operation at altitude. Analysis revealed that the engine fuel-flow-to-N2 gain at the observed frequency of oscillation was lower than predicted and that the phase lag of the engine was greater than expected. Furthermore, review of altitude accelerations from low power revealed an initial sluggishness, followed by a significant overshoot beyond the demanded NDOT, as illustrated in Figure 6.

Investigation of the fuel delivery system components downstream of the HMU identified that these phenomena occur when the secondary fuel nozzle manifold assembly is partially filled. The LF507-1F utilizes a primary/secondary nozzle manifold system, as shown in Figure 7. The primary manifold assembly uses fuel-blast nozzles to provide atomized fuel in the low flow regions. At approximately 220 PPH fuel begins to flow into the secondary manifold assembly, which uses low-pressure-drop air-blast nozzles for atomization. Depending on the amount of flow, the secondary manifold may fill up entirely or stabilize with the fluid level at any intermediate position. Fuel nozzles above the fluid level provide no flow output to the combustor.

As fuel flow is increased from a partially filled state, the majority of flow increase initially fills up more of the manifold piping rather than exiting through the fuel nozzles. The resulting NDOT acceleration rate falls below the demanded level and the NDOT governor commands further increases in fuel flow in an attempt to compensate. When the manifold fills completely, all metered flow enters the combustor, resulting in a large step increase in burned fuel flow. This increase causes a large upward spike in actual NDOT, overshooting the acceleration schedule and posing a surge margin risk.

Once the manifold dynamics were understood, the non-real time and real time simulations were modified to include these effects. A strategy of introducing non-linear gain scheduling when it is estimated that the manifold is not full reduced loop gains for steady state operation while maintaining high gains for large scale transients. In addition, the acceleration schedule and flight idle speeds were adjusted to reduce the magnitude of the NDOT spike to an acceptable level.
Performance Engineers specified that transient interstage bleed problem for the transient interstage bleed control laws. The coarse speed measurement resolution posed more of a problem for the transient interstage bleed control laws. These constraints consisted of an NDOT measurement resolution of approximately 2.0 %/second (0.1 % N2 quantization / 0.048 sec), the computational limitations of the 8-bit fixed point microprocessor, and the 48 millisecond computer cycle time.

A slave datum NDOT governor arrangement, as shown in Figure 8, was selected to best accommodate these constraints. The controller integrates the NDOT demand and compares the result to measured N2 speed to generate an error signal. This provides a design mathematically equivalent to a traditional NDOT-error-based controller, shown in Figure 9, but simplifies the implementation of the fixed point arithmetic and eliminates the effective half-cycle delay and associated phase lag of the digital derivative calculation.

**NDOTDEMAND**

\[ \text{STATE ESTIMATOR} \]

\[ \text{FLOW} \]

\[ \text{NDOTDEMAND} \]

\[ \text{WFDEMAND} \]

\[ \text{K} \]

\[ \text{NDOTMEASURED} \]

\[ \text{N2MEASURED} \]

\[ \text{I} \]

\[ \text{S} \]

**Figure 8: LF507-1F Slave-datum NDOT Governor**

NDOT tracking error is an ineffective indicator of surge. The manifold fill effects discussed earlier cause large NDOT errors in the partially filled manifold region, which would lead to false surge detections with systems based on NDOT error. In addition, it was found that actual NDOT response is not predictable because the relative loss of gas generator turbine output torque versus compressor load is not consistent during surges. The actual N2 speed can increase, decrease, or remain constant depending on this torque balance, resulting in missed detections of actual surge events. P3-based designs were also found to be ineffective. The attenuation of rapid changes in the P3 signal due to line accumulator effects and the 48 millisecond FADEC cycle time would have resulted in inability to discern the P3 pressure spikes typical of engine surge without a high false alarm rate.

**Figure 9: NDOT-Error-Based Governing Loop**

The FADEC schedules are designed to provide surge-free operation throughout the flight envelope for the life of the engine. However, unforeseen abnormal operating conditions can cause an engine to surge. Because an NDOT controller adjusts flow to achieve the desired acceleration rate, it will tend to reinforce a surge by increasing fuel flow during the surge. Therefore, the control includes logic to recognize and recover from locked-in engine surges.

One challenging aspect of this program was the development of reliable surge detection and recovery logic. The design goal was to detect and recover from locked-in surges with a 0% false alarm rate. Unlike detection systems based on P3 or NDOT error, the LF507-1F system detects surge based on the response of measured N1 and EGT. This design has demonstrated 100% successful detection of locked-in surges during flight testing in which surges were deliberately induced. Although not a design goal, the logic also demonstrated greater than 65% successful detection of severe (3-pop) self-clearing surges. Equally important, the logic has demonstrated a 0% false alarm rate to date.

An investigation of the engine response to surge revealed a simultaneous rapid decrease in N1 and a sharp rise in EGT. This is consistent with the physics of surge: the loss or reversal of core airflow causes high fuel:air ratios and a corresponding increase in EGT while the loss of power turbine output torque without a corresponding loss of fan load results in a rapid deceleration in fan speed. Although step increases in engine bleed extraction cause a similar effect, the response to a multiple-pop or locked-in surge event was found to be distinctly different and unique.

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The selected means of surge detection therefore relies upon recognition of a sustained decrease in N1 combined with a sustained increase in EGT. The surge detection algorithm calculates time derivatives of N1 and EGT, filters the derivatives to remove unwanted signal components, and compares the filtered derivatives to predetermined thresholds. A surge condition is declared and the surge recovery routine is initiated when the filtered signals exceed the thresholds.
simultaneously for a preset period of time. Figure 10 presents detection of a typical locked-in surge.

![Figure 10: Response of N1DOT and EGT DOT During a Surge Induced by Overfueling at 31 K feet. Surge Occurs at 0.0 seconds.](image)

**LF507-1F FADEC Diagnostic System:**

High dispatch reliability and system maintainability were two primary goals of the LF507-1F FADEC system. Fault tolerance for high dispatch reliability is provided by using redundant sensors, protecting critical algorithms with backup algorithms, and graceful degradation techniques for those cases in which no backup sensor or algorithm exists. Faults accommodated by these means are soft faults.

Multiple sensors for critical signals (N2, PLA, etc.) provide fault tolerance. The EGT biasing calculation, based on measured EGT, P1, and P3 is backed up by an analog circuit using a T1-based algorithm. This algorithm provides a slightly less accurate biased EGT reading to the cockpit in the event of a P1 or P3 transducer or microprocessor failure. The analog algorithm is backed up by a digital T1 biasing algorithm to protect against analog circuit failures in combination with P1 or P3 sensor failures.

The surge detection algorithm discussed earlier is backed up by a WF/P3 limiter to provide a measure of surge protection after an EGT sensor failure. The metering valve positioning loop employs a "step count" routine to continue to position the metering valve stepper motor and meter fuel after a failure of the metering valve feedback sensor.

Graceful degradation techniques (selective loss of certain control functions) are used to provide as much system functionality as possible after failures that are not protected by duplicate sensors or backed up by other control algorithms. If a failure is such that auto mode control is no longer possible (a hard fault), the system automatically reverts to the dispatchable hydromechanical manual mode.

The goal of the FADEC fault detection logic design was to detect as many faults as possible consistent with minimizing false alarms. Thorough troubleshooting procedures in the maintenance manuals provide coverage for troubleshooting of system problems not detected by the FADEC.

Prevention of false alarms was the priority because false alarms unnecessarily increase the cost of aircraft ownership and operation. False alarms limit dispatchability and cause canceled flights when nothing is actually wrong and lead to unnecessary replacement of fully functional hardware. More importantly, they cause maintenance personnel to lose faith in the FADEC diagnostics and troubleshooting procedures and resort to individual, unproven "trial and error" troubleshooting, increasing maintenance time and costs. These issues are critical in the regional airline market, where maintenance facilities and capability may be limited compared to the major airlines, and where even slight delays result in canceled flights and lost revenue.

The potential for false alarms was minimized through several approaches. The Interdependent Logic Review was an essential tool in the diagnostic logic design process. Other approaches that provide outstanding fault coverage while minimizing false alarms are discussed below.

Input signal reasonableness tests consist of signal range tests and signal comparison tests. Range tests validate input signals by checking that the signal falls within a reasonable range. This range is varied with engine condition to provide enhanced fault coverage. Comparison tests validate an individual signal against similar signals (PLA 1 versus PLA 2, etc.) or against several dissimilar signals (N2 versus a combination of N1/EGT/PLA, etc.). Fault conditions must exist for a specified period of time before being considered an actual fault.

Where possible, additional criteria were added to fault detection logic. As an example, for fault detection purposes a running engine is recognized when N2 exceeds 48% and PLA exceeds 8 degrees for 3 consecutive computer cycles instead of simply when N2 exceeds 48% for 1 cycle.

It is significant that signal "rate-of-change" reasonableness tests are generally not used. Rate-of-change tests, which validate signals by checking that the signal rate of change does not exceed a predetermined level, have shown a high false alarm rate on previously fielded Lycoming engines, requiring in service modifications. Instead, FADEC input circuit hardware was designed to ensure that the more probable faults cause out of range conditions detectable via range tests. Where necessary, comparison tests were added to ensure the needed fault coverage and control loops were made less sensitive to unrealistic rate-of-change inputs. This provided thorough fault coverage and protection without the signal rate-of-change testing and the corresponding high false alarm rate.

Low cost, easy to follow fault annunciation and straightforward maintenance manual troubleshooting
procedures are integral parts of the LF507-1F FADEC diagnostic system. A soft fault indicator is mounted near the engine oil tank dipstick. The magnetic on/off indicator is checked by maintenance personnel during the daily oil level checks and presence of a soft fault is noted. Hard faults are announced to the cockpit via a hard-wired discrete. Soft and hard fault indications are also transmitted over the ARINC 429 data bus to the airframe.

The aircraft is dispatchable with a soft or hard fault, therefore no immediate action is required after detecting a fault. At a suitable time, maintenance personnel check the hexadecimal fault display on the ECU. This hexadecimal display shows a code or series of codes identifying specific maintenance procedures in the maintenance manuals. By varying throttle position, maintenance personnel can access hexadecimal codes for only current faults or for all faults since the last maintenance action.

Each maintenance manual procedure is a short, simple-to-follow procedure that leads to identification and replacement of the failed component. As mentioned earlier, there are a group of maintenance procedures for diagnosing pilot-observed problems that are not accompanied by a corresponding hexadecimal code.

In addition, a more detailed fault history is stored in non-volatile memory. This detailed fault record can be accessed by Lycoming field service representatives using a laptop PC maintenance system for customer assistance in resolving recurrent or hard-to-solve problems.

Maintenance costs are related not only to rapid and accurate identification of failed components, but also to the reliability and accessibility of these components. Where possible, all system components are mounted in benign environments for longer life. All components are readily accessible and easily replaceable for reduced maintenance costs. For example, the interturbine temperature probes used on the ALF502 have been replaced with exhaust gas temperature (EGT) probes for the LF507-1F. These EGT probes reside in a cooler environment and sense a lower temperature (exhaust versus interturbine gas temperature) for increased reliability. They are also much more accessible and easy to change than the previous interturbine temperature probes.

CONCLUSIONS

FADEC engine control brings large turbofan operability and maintainability benefits to the regional jetliner market. Developing a FADEC system for a regional jetliner turbofan market includes several unique challenges. Low system acquisition and development costs are essential in this market, much more so than in the large turbofan market. High dispatch reliability, low maintenance costs, and simple maintenance procedures are critical to the profitability of regional airlines, again more so than the major airline market.