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DEVELOPMENT PROGRAM OF A FULL AUTHORITY DIGITAL ELECTRONIC CONTROL SYSTEM FOR THE T55-L-712E TURBOSHAFT ENGINE

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ABSTRACT

Conventional engine control systems for turbine-powered rotorcraft have become increasingly complex in the process of striving for optimized performance of the power plant and aircraft. Traditionally, the only method of achieving this goal was to increase the level of functional sophistication within the control through nonelectronic techniques.

Using a current RAF development application as an example, this paper reviews the basic requirements for incorporation of a full authority digital electronic control system on a twin-engine military helicopter. Component configuration of the design is discussed which utilizes the latest concepts in electronic technology. Unique operational features and installation details of the engine control system are summarized; such as maintainability, diagnostics, history recording, environmental capability, engine installation and aircraft integration. The functional performance and technical details of the electronic control are described relative to fulfilling the particular requirements of a tandem rotor helicopter. Finally, in order to evaluate and optimize engine control modes, closed-loop computer simulations are utilized as an analytical tool prior to aircraft flight testing to ensure the original design philosophy and goals of the program would be satisfied.

1. INTRODUCTION

For approximately thirty years, regulation and operation of gas turbine-powered rotorcraft have been satisfactorily accomplished with hydropneumatic and hydromechanical engine control systems. However, during this time period, the natural evolution of fuel control systems produced mechanical and electronic hybrid descendents that became significantly more costly and complex than their ancestors. Designers have also discovered there is a practical limit to the level of sophistication for these control systems relative to installation volume, weight, accuracy constraints, and more importantly, the inability to implement complex control functions or to provide an interface with aircraft requirements.

As an example, a typical multi-engine rotorcraft, utilizing state-of-the-art hydromechanical control systems, may exhibit the following limitations or problems:

- Marginal starting during hot relights and cold ambients
- Slow or mismatched engine acceleration time
- Engine compressor stall or surge
- Mismatch of engine torques under load
- Rotor speed droop during transient maneuvers
- No safety features or failure mode protection
- No self-check or diagnostic capability
- Lack of engine history recording
- High pilot and cockpit work load

A modern solution to this dilemma has been the introduction of the full authority digital electronic control (FADEC) for both fixed and rotary wing applications. For the first time, an engine control system has the capability to self-check and diagnose itself, to record and store information, to interface with the real world and to make intelligent decisions based on an accurate transfer of data.

2. DEVELOPMENT PROGRAM

A collaboration was established between Avco Lycoming TEXTRON and Chandler Evans Control Systems Division of Colt Industries Inc to provide a modern FADEC system that would employ the latest concepts in electronic control technology and would be suitable for either turbofan or turboshaft engines.

To take advantage of this innovative configuration, a technical proposal was submitted to the UK Ministry of Defence (MoD) describing a full authority digital electronic control system for the RAF Chinook HC Mkl medium-lift helicopter manufactured by Boeing Vertol (Figure 1). The rotorcraft is powered by two Lycoming T55-L-712E turboshaft engines (Figure 2) currently employing conventional hydromechanical fuel controls.

Lycoming was subsequently awarded a contract in December 1985 from the Ministry of Defence to develop and certify a FADEC system for the HC Mkl/T55-L-712E application. Although the configuration is based on a substantially identical design currently being developed by Chandler Evans for the Lycoming ALF 502 turbofan engine, the program is extremely fast-paced with aircraft flight tests scheduled for the latter part of 1987.

Figure 1
RAF CHINOOK HC Mk1 HELICOPTER

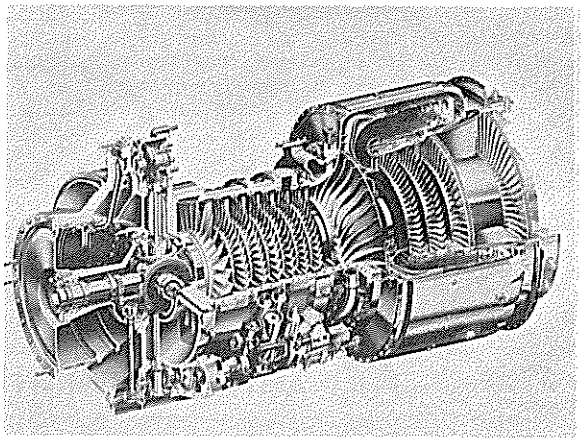


Figure 2
LYCOMING T55-L-712E TURBOSHAFT ENGINE

3. COMPONENT CONFIGURATION

The current engine control system used on the RAF HC Mkl/T55-L-712E application represents a 30 year old design philosophy that has historically exhibited certain limitations or problems. Using state-of-the-art digital technology, the Chandler Evans Model EMC-32T electronic control system was designed to provide improved functional performance, reduced pilot work load, increased system reliability, reduced maintenance tasks and a very cost effective system as compared to the existing control.

The engine-supplied FADEC system, shown in Figure 3, consists of three major elements that have been designed to minimize the functional and mechnical differences from the existing engine/airframe installation.

- An airframe-mounted digital electronic control unit (DECU) that also contains a built-in diagnostic fault display window and bi-directional serial data communication connector.

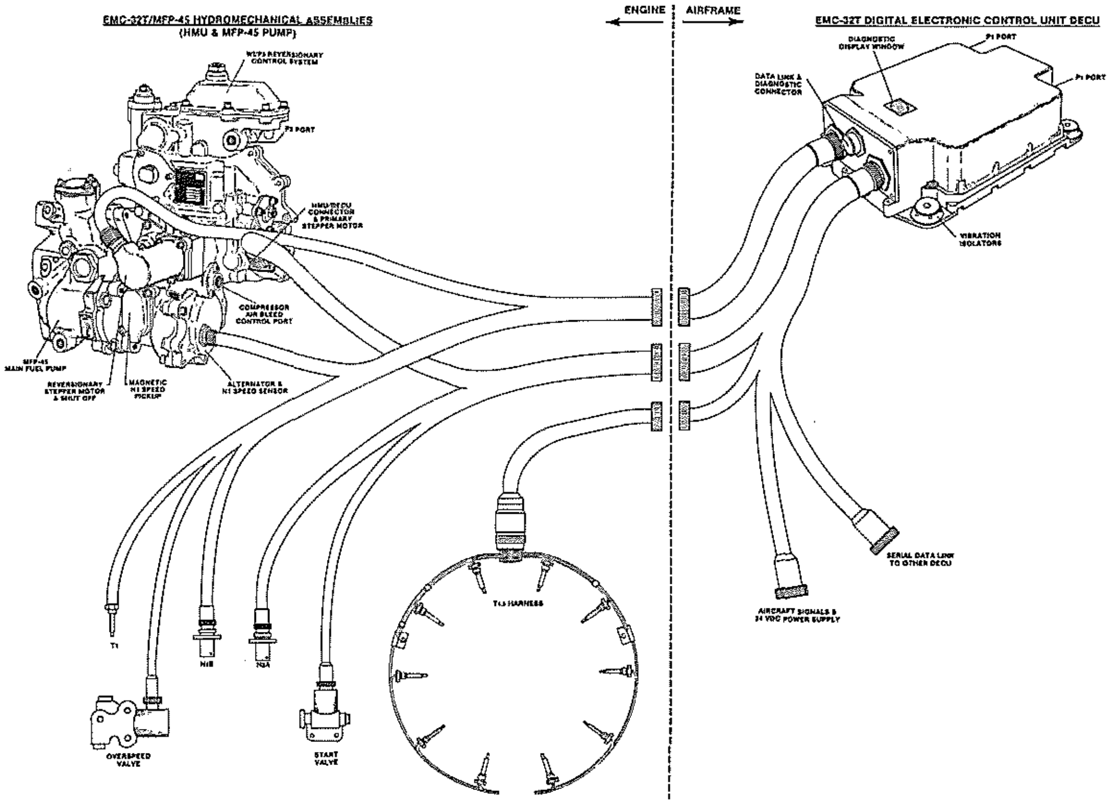


Figure 3
FULL AUTHORITY DIGITAL ELECTRONIC CONTROL SYSTEM

- An integrated fuel metering unit (HMU) which mounts in place of the existing hydromechanical fuel control. The new package includes a gearbox-driven high pressure fuel pump and alternator in addition to an electromechnical primary metering unit and backup reversionary fuel control.

- A set of electrical harnesses which connect the electronic control, electromechnanical components, engine sensors and airframe signals.

The EMC-32T FADEC system, depicted in the block diagram of Figure 4, describes component configuration and shows the relationship between control/engine/airframe interface signals.

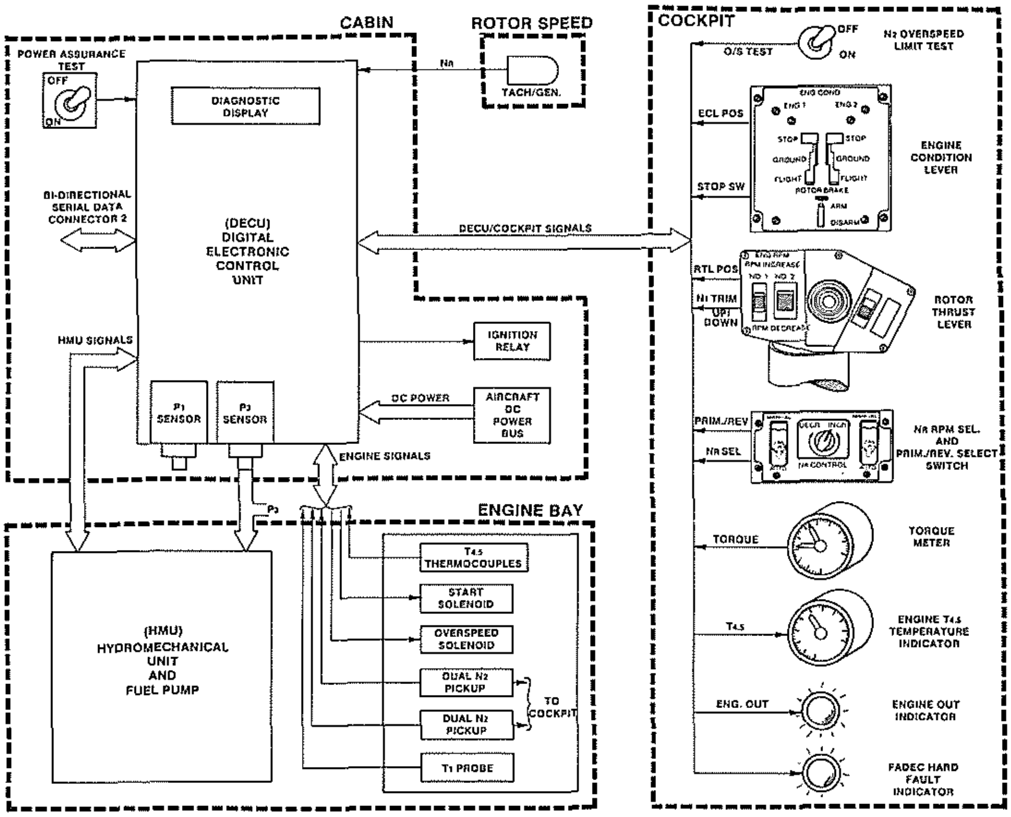


Figure 4
EMC-32T ENGINE/AIRCRAFT FADEC INTERFACE BLOCK DIAGRAM

4. OPERATIONAL FEATURES

In addition to offering outstanding operation of the total power plant/aircraft combination by providing precise control and limiting functions to optimize system performance, the EMC-32T FADEC offers important features not currently available with hydromechanical fuel controls.

Maintainability and Diagnostics

The incorporation of built-in test and diagnostic features in the FADEC facilitates direct diagnosis and maintenance of both the DECU and electromechanical components within the HMU. Readout, via a two-digit hexadecimal display on the DECU, aids maintenance personnel in identifying faults experienced during the last engine run and to isolate a particular fault that can be identified to a line replaceable unit (LRU).

More specific fault identification and cumulative fault history can be examined using separate test equipment. The FADEC system provides on-condition maintenance, with no scheduled overhaul time. Additionally, the system offers module interchangeability and the elimination of all field adjustments.

History Recording and Health Monitoring

Provisions have been made within the FADEC for the addition of preflight and post-flight engine data gathering features to provide prognostics and high level engine health monitoring functions.

- Time, temperature and cycle counts for timed bands of engine operation.
- Duration and extent of engine limit exceedance both during normal operation and emergency conditions.
- Engine failure detector warning to reduce pilot reaction time.
- Power to hover assurance check for a specific ambient condition.

This information will be supplied by the FADEC via illumination of cockpit lights on the maintenance panel, interrogation with a comprehensive hand-held diagnostic terminal, special activation of the hexadecimal fault display window, or complete extraction of historical data via a bi-directional serial data communication link connected to a compatible external terminal.

Environmental Compatibility

The EMC-32T FADEC system is designed to meet stringent environmental requirements relative to ambient temperature, vibration levels, flight maneuver forces and electromagnetic environment.

The electronic assembly is housed in an environmentally sealed cast aluminum enclosure and it has been designed to withstand an operational ambient range from -54 degrees C to +85 degrees C. The DECU is designed to meet the Electromagnetic Compatibility (EMC) requirements of MIL-STD-461B and FS(F) 510. The aluminum enclosure provides shielding for the circuit boards and internal components, while a ground strap maintains an electrical ground path from the enclosure. EMC filtering is used to bypass all electrical transients and noise and internal shielding provides isolation between EMC filtering, power supply and control circuit areas. Protection against lightning-induced transients is through the selection of filtering components with sufficient surge ratings.

The hydromechanical fuel metering unit and pumping system mounts on the accessory gearbox and is compatible with the helicopter turbine engine environment. The HMU can operate at ambient and fuel temperatures of -65°F and elevated temperatures of 155°F at the engine fuel inlet and an ambient of up to 260°F. The fuel metering system also operates with contaminated fuel in general compliance with MIL-E-5007C supplied through the engine fuel filter. The

HMU is designed to meet vibration inputs up to 10 G's and impact/shock loads up to 20 G's. The environmental sealing capability of the HMU has been designed to meet the requirements for explosion-proof in general compliance with MIL-STD-810 and a fire test in which a 2000°F flame is directed at the fuel metering housing for a period of five minutes.

5. INSTALLATION DETAILS

Engine Installation

The HMU fuel metering and pumping unit mounts on the engine gearbox in the exact location of the present hydromechanical fuel control and fuel pump. Connections to the HMU include four fuel lines at the inlet, discharge, starting and seal drain ports; three electrical connectors for the primary control, reversionary control and alternator; and two pneumatic lines for the P3 sensor and the compressor interstage air bleed actuator signal. With the exception of electrical connectors, only minor changes to the current engine plumbing are required for this installation.

The dual path engine electrical harness employs flight separation of FADEC control signals for vulnerability considerations. The harness covering is a convoluted, flexible tube constructed of Teflon that permits a repairable configuration relative to replacement of both wire runs and connectors. The design offers water resistance, integral shielding, excellent maintainability and very high reliability.

Aircraft Installation

The digital electronic control unit will be mounted on the aft fuselage ceiling utilizing vibration isolators. Connections from the DECU to the engine/aircraft interface panel include a compressor discharge pressure (P3) pneumatic signal line and three electrical connectors that communicate to the HMU and engine sensors, the power turbine inlet temperature (T4.5) thermocouple harness, the airframe/cockpit signals and the bi-directional serial data communication output connector.

A survey of the airframe/engine interface hardware reveals that many cumbersome electrical components, such as control boxes, actuators, droop eliminators and relays, can be deleted or functionally incorporated within the FADEC system via an electrical harness (Figure 5). To preserve the configuration of the current HC Mk1 cockpit layout, existing instrumentation, engine condition quadrants and thrust control levers have been retained.

1. POWER TURBINE N_2 CONTROL ACTUATOR (2)
2. GAS PRODUCER N_1 CONTROL ACTUATOR (2)
3. ENGINE GAS PRODUCER N_1 CONTROL BOX (2)
4. ENGINE CONDITION CONTROL RELAY (2)
5. EMERGENCY ENGINE CONDITION CONTROL RELAY
6. ENGINE CONDITION CONTROL RESISTOR
7. ENGINE POWER TURBINE (N_2) CONTROL BOX (2)

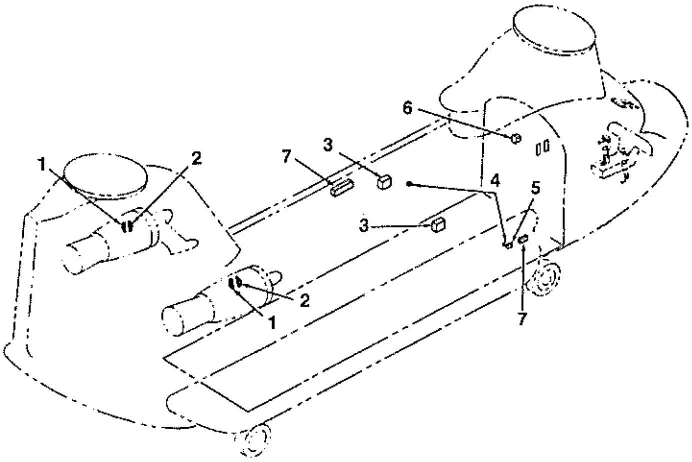


Figure 5 HC Mk1 AIRCRAFT HARDWARE DELETIONS

Preliminary pilot functions, such as power selection and thrust control, are operationally identical to the present aircraft whereas new secondary functions, such as power turbine speed selection, fault indication lights and reversionary control switches are incorporated into existing cockpit panels that have been vacated by obsoleted functions. Because airframe modifications will be limited to minor changes within the cockpit, the same operating modes are retained and pilots will have to go through an extensive retraining process.

6. FUNCTIONAL DESCRIPTION

The FADEC system will provide all functions available in the current hydromechanical control at a superior level of performance. In addition, it incorporates advanced features to enhance operation and performance in both the T55-L-712E engine and the HC Mk1 helicopter while reducing pilot and cockpit work load.

Although advantages of FADEC's have been well documented over the years, outstanding performance highlights of the EMC-32T control system are summarized in the following sections.

Engine Starting

Incorporation of an electronic control system permits engine operation at a near optimum start mode. Control of engine acceleration rate, or time derivative of N1 speed (NDOT) with measured power turbine inlet temperature (T4.5) limiting, results in a consistent, predictable start.

Engine Acceleration and Deceleration

The control mode for both accelerating and decelerating the engine is an ambient temperature (T1) and altitude-biased (P1) closed-loop acceleration rate control (NDOT/P1).

Surge Avoidance and Recovery

The EMC-32T control uses a time derivative of compressor discharge pressure (P3DOT) to detect the onset of surge. When P3DOT drops during an engine acceleration or NDOT stagnates during a start, a surge detector circuit is activated. The compressor bleed valve is snapped open, the engine is decelerated momentarily and then reaccelerated to the new operating condition at a recovery rate proportional to the severity of the surge.

In normal operation, the FADEC acts to avoid surge through its precise control of the engine during the transient conditions where surge is most likely to occur. Altitude and inlet temperature compensation of the closed-loop NDOT control mode, together with the closely coordinated control of the compressor interstage bleed, provide maximum surge margin for the engine throughout the flight envelope.

Power Turbine Speed Control

To overcome inherent rotorcraft problems such as transient speed droop, power recovery and torque overshoots, the FADEC system selects rapid anticipation of power and provides fast transition from the isochronous steady running line to the engine acceleration/deceleration fuel flow limits. Equally important to helicopter handling qualities is a smooth engine torque application. Therefore, control system gains must be high to restrict rotor speed droop, but also need to be low at specific times to preclude transient excursions which also affect pilot work load.

Torque Matching and Power Management

Communication of electrical torque meter signals from each engine allows the electronic control to provide an accurate and responsive torque matching function. Backup protection is provided by matching gas generator speeds. Therefore, if a torque signal should fail, both FADEC systems switch over to the N1 speed matching mode.

Rotor Thrust Control

The EMC-32T FADEC uses sophisticated control logic to optimize rotorcraft performance during various transient maneuvers such as waveoffs or quick turns. This is accomplished by utilizing the decoupled decay rate of rotor speed (NRDOT) to proportionately demand a gas generator acceleration rate during and immediately following a split needle condition. By utilizing rotor speed decay anticipation, a significantly improved transient rotor speed control system can be obtained. The proposed NR rate anticipator does not attempt to predict rotor load, it simply gives the engine a head start and then allows the more intelligent governor logic to assume control.

Reversionary System

The control system provides a digital microcomputer-based electronic reversionary control, with hydromechanical backup, in the unlikely event of a failure of the primary digital control. The reversionary control modulates required engine Wf/P3 ratio units via a dedicated stepper motor in the HMU which is optimized by electronic trimming devices.

To summarize, the reversionary control system provides full engine power modulation, surge, overtemperature and overspeed protection, as well as N2 speed governing, and incremental N1 speed trimming to compensate for various operating conditions, including deteriorated or damaged equipment. Therefore, the pilot has the capability to pull rapid Rotor Thrust Lever or RTL maneuvers and retain considerable aircraft maneuverability while in the reversionary mode.

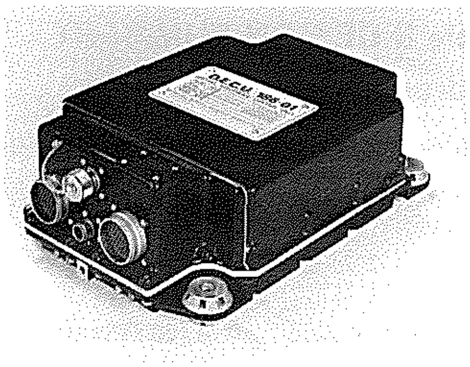
7. DESIGN SUMMARY

A previous paper (Reference 1.) provided a technical discussion concerning internal details of this system. However, the reversionary system electronics has been expanded and is now implemented using digital technology. This reversionary system includes a second channel of digital electronics designed around a 16-bit microcomputer. The reversionary system with its high computational ability provides additional diagnostics and fault management, as well as speed governors, temperature limiters, acceleration and deceleration control included in the original design. Tables 1 and 2 provide a summary of design details of this control system, including the reversionary control.

Table I DESIGN SUMMARY

Digital Electronic Control Unit

Weight.	10.7 lbs. (4.9 Kg)
Installation	Airframe-mounted, *vibration isolators at* mounting points.
Construction	Cast aluminum housing and cover with EMI seal
Ambient Temperature	-54 Degrees C to +85 Degrees C
EMC, Lightning Compatibility	Per MIL-STD-461B, FS(F)457 & FS(F)510
External Connectors	MIL-C-83723, Series 3
Power Supply	Switching mode pulse width modulated type using stamped aluminum shield.
Circuit Boards	Four multilayer boards
P1 Transducer	Bonded strain gage bridge
P3 Transducer	Bonded strain gage bridge
Internal Connections	Multilayer flexible cables
Reversionary Control	Electronic RTL vs. N1 with T4.5 overtemp. limiting & N2 speed governing. Operates through Wf/P3 hydromechanical.



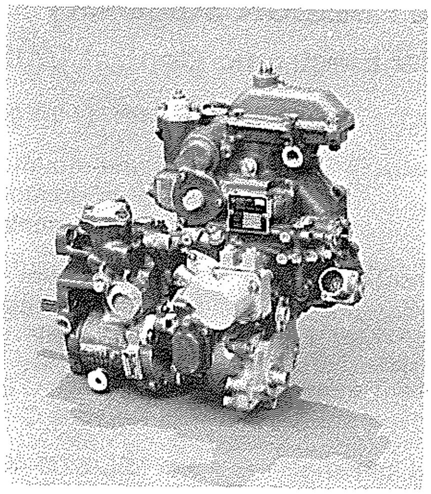
DIGITAL ELECTRONIC CONTROL UNIT

Primary Computer	Intel 80186 Microprocessor based design
RAM	2K x 16 Bits, expansion to 4K
EPROM	32K x 16 Bits, expansion to 64K
EEPROM	2K x 8 Bits
Reversionary Computer	Intel 8097
RAM	Internal 256 x 8 Bits External 2K x 16 Bits
EPROM	8K x 16 Bits
Diagnostic Display	2 Hexadecimal digits
Serial Communication	Via RS423 data port
Overspeed Protection	Interface with engine fuel reducing valve

Table II DESIGN SUMMARY

Hydromechanical Unit

Weight	31.6 lbs. (14.4 Kg)
Installation	Engine-mounted, in *place of current* hydromechanical control.
Gear Pump Rating	8,100 PPH at 700 PSID 100% N1 (4,200 RPM) 675 PPH at 150 PSID, 10% N1 (420 RPM)
Boost Stage	Pressure Regulated Jet Inducer 770 - 9,260 PPH
Dry Lift	1 Foot minimum at 15% N1
Vapor Liquid Ratio	0.45 at engine inlet
Metering Valve:	Rotary flat plate design
• Rating	0 - 2,470 PPH
• Electromechanical Drive	4-phase stepper motor (2)
Compressor Air Bleed:	
• *Automatic Mode*	*Solenoid Valve*
• Reversionary	Hydromechanical valve
N1 Engine Speed Sensing:	
• Primary	Magnetic Sensor
• Secondary	Alternator winding
• Reversionary	Hydromechanical
Reversionary Control	Automatic or pilot-selected. Maximum and Minimum Wf/P3, Wf & P3 Limits.
Alternator	Meets DECU power requirements at idle and above.



HYDROMECHANICAL CONTROL UNIT

8. CLOSED-LOOP SIMULATION TESTING

The design and development of a modern FADEC system today employs a number of computer-aided tools. These include Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM), together with group technology for hardware design. Engineering computer systems operating in scaled time are used for development of control design algorithms, software development and dynamic response analysis. Another important area in which Chandler Evans has employed a high speed digital computer and associated interface hardware is in the closed loop testing of FADEC's. The closed loop testing exercises the entire FADEC system in "real time"; i.e., typically 2-4 seconds of cycle time, which is fast enough to appear as continuous. This closed loop testing includes simulations of required single/ dual engines, helicopter and all interface sensors.

Simulation Test Procedure

The simulations used employ "excess torque" engine and helicopter rotor models. These models were derived from previous control programs and adapted to the T55/HC Mkl application. Simulation of the rotor system required changes since the original model accommodated only one articulated rotor while the HC Mkl aircraft has two. The engine model simulation was also modified to include effects of the T55 interstage compressor air bleed system.

All engine performance data used in the simulation were supplied by Lycoming. Maps of all engine variables were provided in pairs, giving engine characteristics when the interstage compressor bleed band is completely open and when it is completely closed. The bleed band actuator was modeled as a first order lag whose time constant is a function of compressor discharge pressure (P3). During bleed transients when the bleed band is neither fully open nor fully closed, engine variables are calculated by linearly interpolating between the bleed open and bleed closed engine maps.

The partials of engine variables, with respect to fuel flow, were provided by Lycoming as a function of core engine speed and percent of over/under fueling. These values were averaged to yield maps which vary only with engine speed.

Constants used in the rotor simulation study were supplied by Boeing Vertol. Data provided included shaft inertias and stiffness, linearized description of lag dampers and rotor load maps. Boeing also supplied actual aircraft flight test data from the current production helicopters to allow performance comparisons.

The simulation with current performance maps and modifications described was then verified by duplicating transients found in the flight test data. Simulation results correlated well with the test data in both transient response characteristics and frequency response, and the model is considered a valid engine/ rotor model for control development testing.

Closed Loop Computer Facility

This test setup used to run these models is centered about a Gould 8780 dual processor computer capable of operating at about 8 MIPS; i.e., Millions of Operations per Second. The other peripheral hardware provides A to D and D to A conversions so the FADEC or FADEC's under test will be operating in a "real" operational environment. The closed loop testing allows demonstration of all control regimes, including:

- Starting
- Acceleration

- Gas Generator Governing
- Deceleration
- Power Turbine and Rotor Speed Governing
- Limiting Functions
- Altitude Performance
- Fault Mode Performance
- One Engine Out Operation

This closed loop testing allows fine tuning of control algorithms and final validation testing of the system, including software, prior to engine or flight testing. In the case of the T55 engine system, it also provides early performance comparison with the existing hydromechanical control system. The closed loop test facility is shown in Figure 6 and a block diagram depicting the hardware is shown in Figure 7.

Figure 6 CECO REAL TIME CLOSED LOOP FACILITY

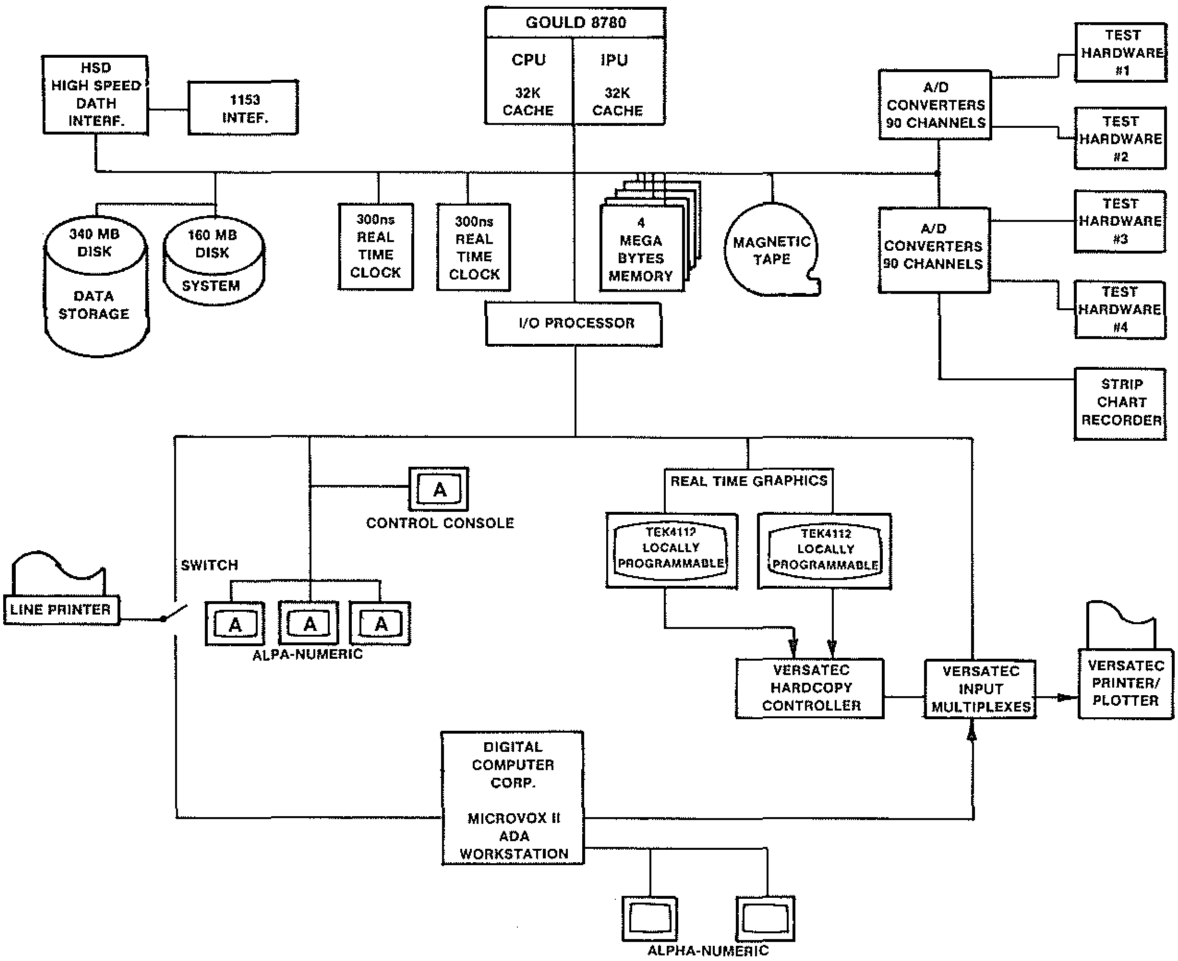


Figure 7 CECO REAL TIME CLOSED LOOP BLOCK DIAGRAM

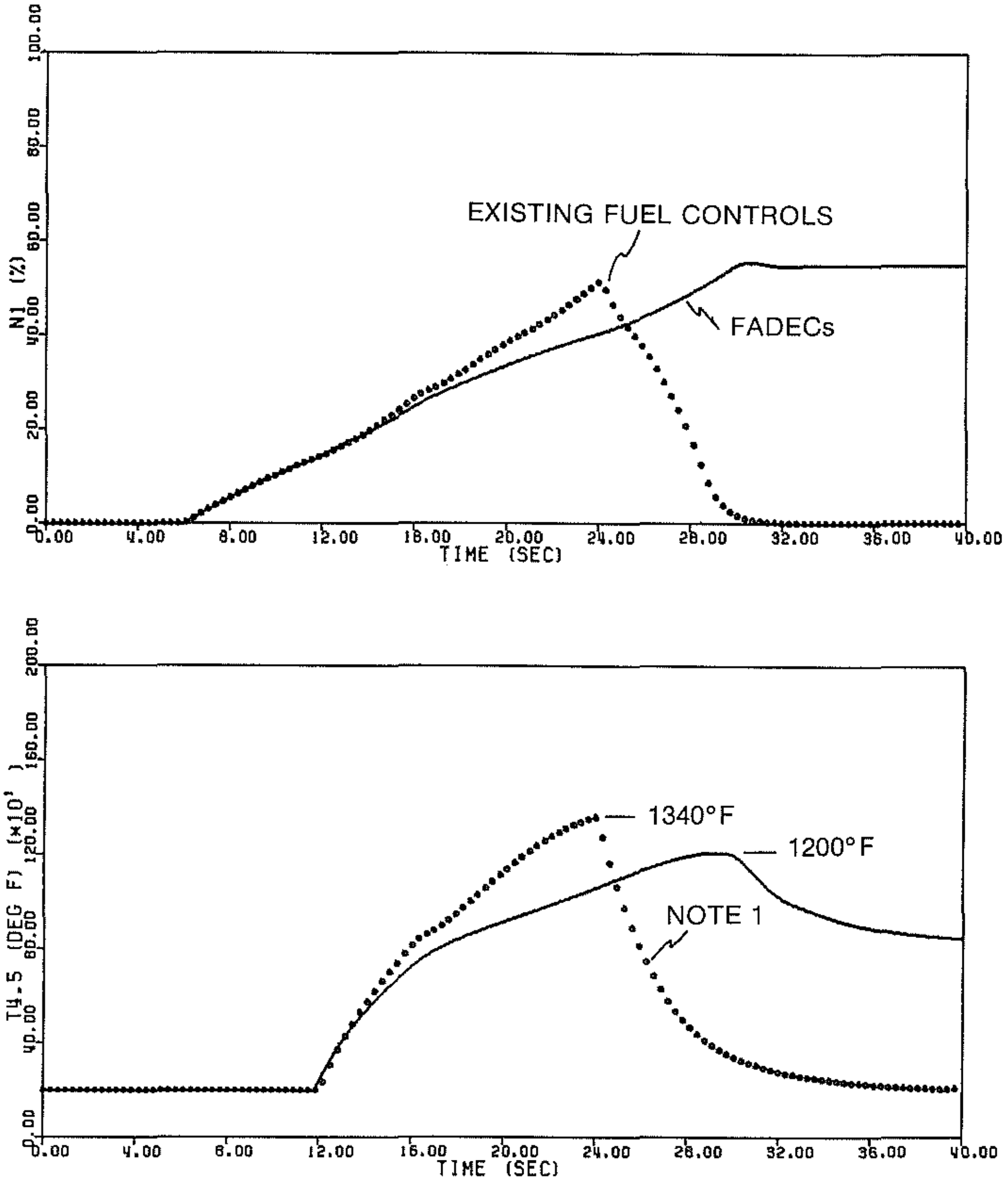
Simulation Test Results

Typical analytical results obtained during control law development, along with comparisons with current hardware in operation, are illustrated in the following figures.

Figure 8 illustrates engine starting performance comparing an aborted hot start of the current hydromechanical control with the NDOT and temperature limited start of the FADEC system.

Figure 9, showing rotor performance during a jump takeoff, compares the old and new fuel control systems. The results clearly indicate the advantages to be gained by employing the EMC-32T FADEC.

Figure 10 illustrates helicopter or free turbine performance during and after a rapid collective pitch related maneuver. This figure highlights the excellent performance of the new FADEC system when operating engines in the primary mode and in the primary and reversionary modes. Results obtained with current hydromechanical hardware are also shown. These results show a 3.8 times reduction in rotor speed droop operating in the primary mode and a 1.7 times reduction with one control in the primary mode and one in the reversionary mode. In addition, the associated rotor or total gearbox absorbed torques are also shown. Figure 11 depicts similar information during and after a rapid collective pitch input from autorotation.



NOTE 1 - Data obtained from AVCO LYCOMING TEXTRON REPORT RUN 1322 NAPC

Figure 8
T55-L-712 ENGINE STARTING PERFORMANCE
EXISTING FUEL CONTROL vs EMC-32T FADEC

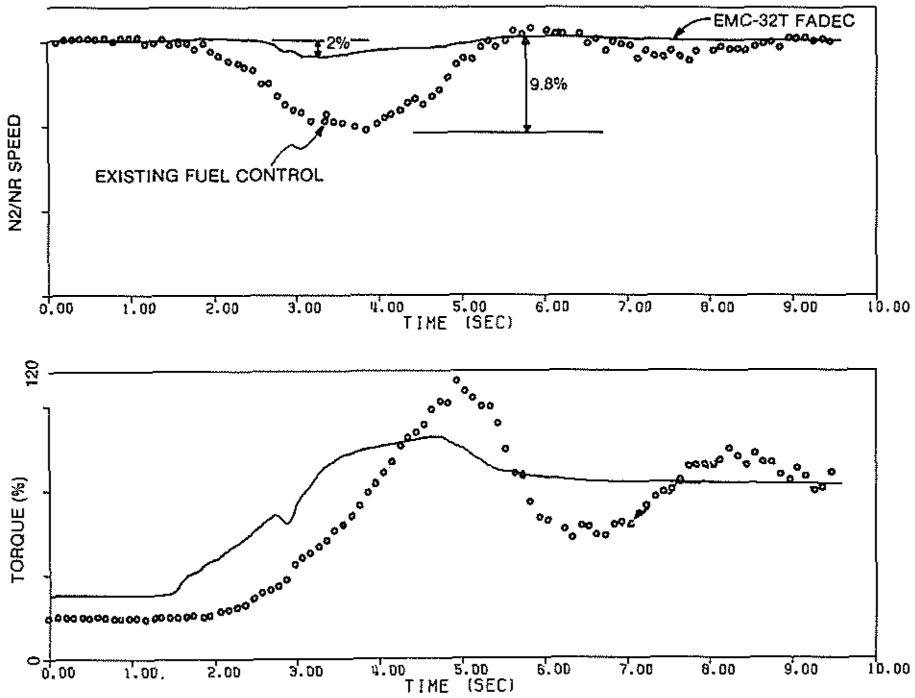


Figure 9 CH-47 ROTOR PERFORMANCE - JUMP TAKE-OFF COLLECTIVE MANEUVER
EXISTING FUEL CONTROL vs EMC-32T FADEC
(60% COLLECTIVE PULL IN 2 SECONDS)

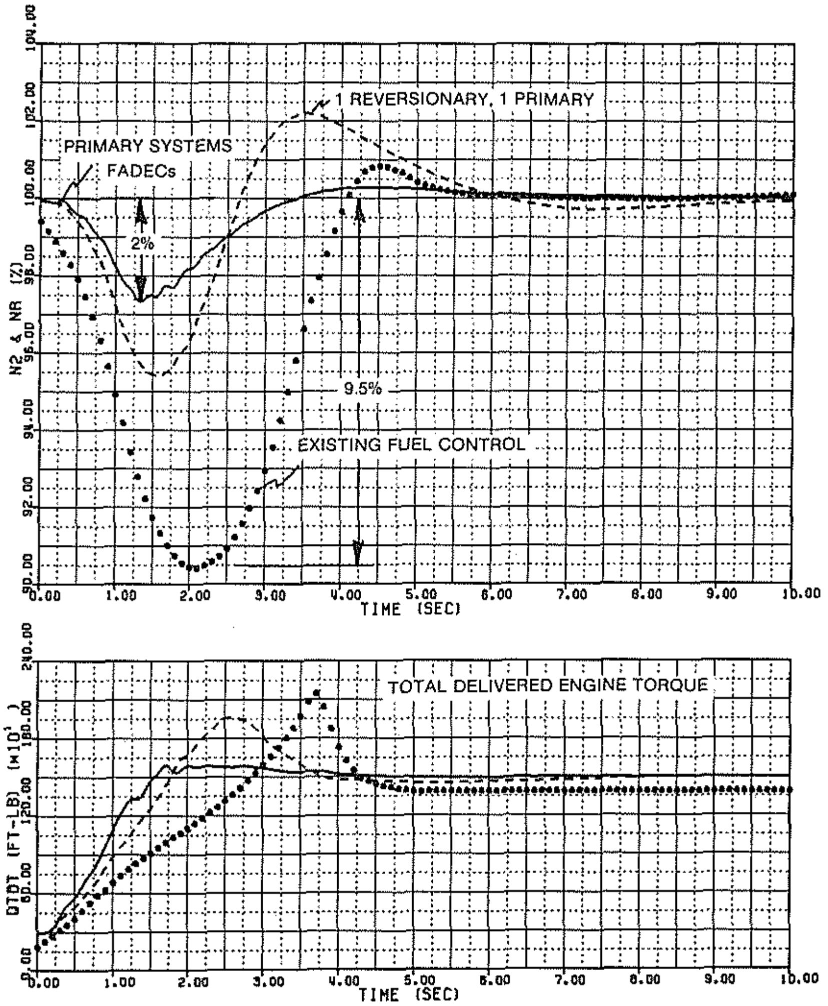


Figure 10 CH-47 ROTOR PERFORMANCE - COUPLED COLLECTIVE MANEUVER
EXISTING FUEL CONTROL vs EMC-32T FADEC
(1 SECOND COLLECTIVE PULL 10% TO 60%)

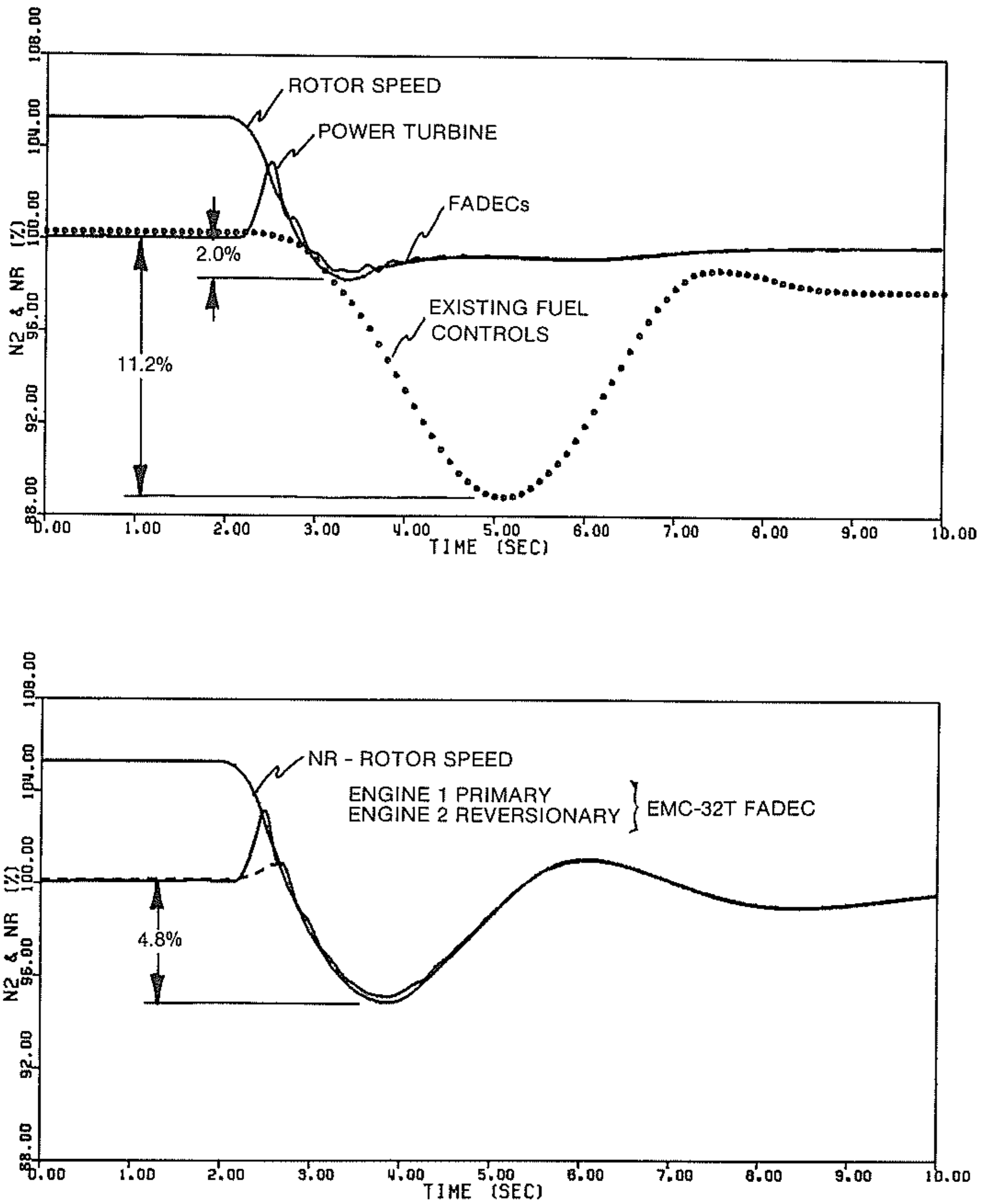


Figure 11 CH-47 ROTOR PERFORMANCE - FROM AUTOROTATION COLLECTIVE MANEUVER
EXISTING FUEL CONTROL vs EMC-32T FADEC
(0 to 70% COLLECTIVE PULL IN 0.5 SECONDS)

9. SUMMARY

Lycoming was recently awarded a contract from the UK Ministry of Defence (MoD) to develop and certify a FADEC system for the RAF HC Mkl medium lift helicopter. The derivative FADEC system utilizes state-of-the-art technology and is based on a substantially identical design currently being developed by Chandler Evans for the Lycoming ALF 502 turbofan engine.

The FADEC system provides on-condition maintenance with no scheduled time between overhaul (TBO), control system diagnostics, complete component interchangeability, elimination of field adjustments and capability for future functional growth and engine history recording functions.

Incorporating an electronic control system on the HC Mkl/T55-L-712E application allows considerable removal of airframe/engine interface hardware which, in turn, will substantially improve reliability and dispatch capability of the aircraft and reduce pilot work load. With a few exceptions, all control/engine/airframe interface signals utilize primary and secondary parameters that require virtually no installation changes to the engine or airframe.

Existing closed-loop test bench simulation equipment is being used as an analytical tool to design, develop and test the electronic control prior to flight testing. A real time model of the FADEC system, engines and helicopter rotor dynamics is programmed on a digital computer. Control system components are operated in a closed-loop fashion to statically and dynamically simulate response from various engine/aircraft flight maneuvers.

A FADEC system comprised of a functionally simple fuel metering unit and a powerful state-of-the-art digital electronic control unit will provide a very cost effective, maintainable and modern technology solution to today's operational problems.

10. REFERENCES

1. D. J. Petro, A. J. Gentile, A. B. Foulds, "A Full Authority Digital Electronic Control System for Multi-Engine Rotorcraft", presented at the Eleventh European Rotorcraft Forum, London, England, 1985