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HELICOPTER ENGINE CONTROL SYSTEM
INTRODUCTION OF DIGITAL ELECTRONIC SYSTEM ON WESTLAND LYNX AND WESTLAND 30 WITH ROLLS-ROYCE GEM ENGINES

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ABSTRACT

The basic requirements and philosophy of a helicopter engine control system are addressed, and a review of the solutions offered during the previous 20 years is presented. Their characteristics due to technological limitations are discussed and in view of these limitations the potential advantages of a digital electronic fuel control system are covered.

An outline of the installation of a Hamilton Standard digital electronic fuel control system on two Westland aircraft types is accompanied by a discussion of the digital control system philosophy and design. The development of the system to meet the particular requirements of two differing Westland helicopter types is covered, with a summary of the engineering tasks required to ensure that the original design philosophy and aims were achieved.

1. INTRODUCTION

The helicopter derives lift together with roll and pitch control from collective and cyclic variation of the main rotor blade angle whilst a constant rotational speed is maintained. The torque of this main rotor is re-acted by the tail rotor which is directly geared to the main rotor. Variation of tail rotor blade pitch provides yaw control.

The basic requirements of the engine control system is automatic response to power demand resulting from input from the pilot and/or auto flight control system to the helicopter main flying control system, in addition it is necessary that the engine control system automatically responds to variation in power demand resulting from gusts, variation in aircraft forward speed, yaw control etc.

The pilot's workload in respect of the total power plant must be minimal, therefore the engine control system must ensure power response rates compatible with aircraft control inputs, and that design rotor speed is precisely maintained throughout the power spectra.

From this it follows that engine control systems are also required to provide :-

(i) Stable power turbine/rotor speed governing over the total power spectrum with minimal transient rpm excursion on rapid power demand or rejection.

(ii) Engine protection in respect of rotational speed and turbine temperature limits.

(iii) Optimisation of engine acceleration/power response rates whilst maintaining adequate compressor surge margin.

(iv) Automatic response of the remaining engine to maximum power in the event of an engine failure.

(v) Precise engine power matching.

(vi) Precise and stable power turbine speed governing in auto rotation and accessory drive modes.

(vii) Control characteristics compatible with rotor start and run up from rest to normal operating speed.

(viii) Minimum cockpit engine control and indications.

Historically, since the introduction of turbine engines in helicopters, these basic engine control characteristics have been broadly satisfied by engine control systems based on the full authority power turbine/rotor speed governing concept (Fig.1). The principle of this is that the engine control system senses power turbine/rotor speed and responds to deviation by corrective change of fuel flow and therefore power output. In order to ensure stability, overall response is in accordance with a predetermined governing droop law. Progressive resetting of datum/rotor speed by suitable interlinks between the helicopter collective pitch control and power turbine governor may provide substantially constant rotor speed.

In general, engine response to demand for rapid acceleration or deceleration due to rapid flight control system demand has been adequate, whilst the engine control system ensured necessary surge margin and power turbine governor response to limit transient power turbine/rotor speed excursions to acceptable values.

Previous and current in service helicopters with gas turbine engines with control functions as previously outlined have employed totally hydromecanical or a combination of electrical analogue and hydromechanical engine control systems.

Examples are Westland Lynx (Fig.2) and initial W30 helicopters with Rolls-Royce Gem engines embodying a hydromechanical system (Fig.3) and Sea King and Wessex which have a combination of electrical analogue and hydromechanical units fitted to Rolls-Royce Gnome engines (Figs.4 and 5).

2. EXPERIENCE

These engine control systems on the current generation of multi engine turbine helicopter have given good operational performance and satisfactory reliability over the past two decades.

There are however areas where the levels of technology within these control systems would preclude total optimisation. These may be summarised as follows :-

(a) Continuous precise matching over the total power spectra in consideration of varying individual engine performance characteristics.

(b) Provision of relatively complex acceleration control to optimise engine response over the flight envelope.

(c) Ready and simple adjustment to accommodate particular installation requirements.

(d) Provision of diagnostic and in-built self checking facilities.

3. REASONS FOR INTRODUCTION OF DIGITAL ELECTRONICS

In addition to being able to carry out the basic functions of the full-authority rotor/turbine speed governing system digital electronic systems have the capability of determining more precise control outputs from consideration of a number of relatively complex inputs, this ultimately optimises total aircraft performance and economy.

The optimisation of engine control and response characteristics over the complete flight envelope is facilitated by extended availability of control functions due to the use of digital electronics. For example, the engine acceleration may be precisely varied in accordance with altitude and ambient conditions.

During development a number of control options for given parameters may be evaluated, resulting in the ultimate selection of control laws most suited to the particular installation.

Additionally, more precise and reliable limiting and protection functions in respect of engine rotational component speeds and temperatures are basic to this type of system. These functions also may be adjusted by relatively simple modification procedures to provide optimisation of system response.

Cost of ownership of a digital system is reduced due to lower maintenance and acquisition costs. Self diagnostic capabilities and monitoring functions give a further improvement over hydro-mechanical and electro-analogue/hydro-mechanical systems.

The electronic outputs from a digital system may also be employed to form inputs to an automatic engine health monitoring system. Relevant information can be processed to provide accurate life cycle fatigue count and engine performance indications to enable operators to extract optimum usage from their aircraft.

4. DESCRIPTION OF SYSTEM INSTALLATION

The Hamilton Standard MACS system was selected and this full authority digital electronic system has been developed by Rolls-Royce in collaboration with Westland Helicopters for use on the Westland 30 and Lynx, both of which are powered by the Gem engine.

The control system comprises two basic units :-

(i) an engine mounted hydro-mechanical fuel control, providing fuel pumping, filtration and management capabilities. (Fig.6).

(ii) An airframe-mounted Engine Electronic Control (Fig.7) to modulate the engine fuel flow via an electrical input to the hydromechanical fuel control, to provide full authority rotor speed governing and also to provide free power turbine overspeed protection by a separate subsystem. (Fig.8).

In the event of a major electrical control component failure, the system is designed to fail freeze - the engine fuel flow and thus power output is then modulated manually via the cockpit Engine Condition Lever.

Pilot control of the engines is provided by the following engine control system inputs. (Fig.9).

(a) Engine condition levers. The Engine Condition Lever provides selection of high pressure fuel cock off, start and ground idle, and flight (electronic unit controlled) mode. In the manual reversion mode this lever provides direct scheduling of engine fuel flow.

(b) Pilot-operated potentiometer controls (Fig.10) are provided for the precise matching of the two engines power turbine speeds, and also for the redatuming of the rotor speed within a predetermined selectable range.

(c) Potentiometers are also provided to facilitate initial basic matching of the individual engines' torque vs NF characteristic to ensure power matching over the full engine power range.

(d) Positive lock in of manual reversion is selectable by means of a cockpit switch. This facilitates pilot training in respect of electronic control failure and also would prevent the effect of an intermittent electronic control system malfunction.

(e) Test switches are provided for verification of correct operation of each engines' power turbine overspeed protection system. Operation of these switches selects a reduced datum within the free power turbine overspeed protection system, resulting in engine shut down from normal operating conditions.

(f) An electrical/collective interlink is provided by means of a potentiometer mounted on the collective flight control (Fig.11). This input to the EEC provides for a substantially constant rotor speed control by redatuming the power turbine/rotor speed in accordance with a predetermined control law.

Each engine control system and associated electrical aircraft interfaces are entirely independent. Failure of any of these inputs to the electronic control system should not significantly affect operation as the system would revert to pre-programmed back up laws. Immediate pilot reaction is therefore unnecessary.

5. CONTROL SYSTEM PHILOSOPHY

The interpretation of the airframe requirements into requirements for the engine control system has produced many solutions as mentioned earlier. A simple approach is often advocated - the "pump and tap" system with as little else as possible being the starting point for the discussions between the controls engineer and the engine designer. However, the foregoing shows that the control system for a helicopter engine is not at all simple, in fact in many ways it is the most demanding control task.

In most fixed wing aircraft the control is effectively open loop, that is the pilot determines directly the system (and hence engine) power demand, with the pilot sensing the requirement for more or less power depending on the flight conditions. Fixed wing aircraft are in general easier to fly than helicopters - the pilot generally having one hand free and control in the vertical plane being essentially indirect. In the helicopter the pilot has a high workload just to fly the machine : the control system has to perform all the functions described earlier in a fully automatic way in flight in a completely safe and certifiable manner. In addition, the control system has to be lightweight, reliable and competitive in terms of first cost and cost of ownership - these are important constraints because in principle the control task can be solved in many ways but not all solutions are cost effective.

The Rolls-Royce Gem engine in its initial Marks was fitted with a hydromechanical control system. When the system was selected for the engine in 1969, reliability was of paramount importance and at that time, although the Rolls-Royce Gnome engine had an electronic (analogue) control with a good standard of performance, the achieved reliability was not good enough to commit the Gem control to electronics.

In 1980 however, with 3 million hours of Gnome control experience and an updated Gnome system in production of proven reliability, Rolls-Royce issued a specification for a first generation digital electronic control for the Gem.

The Hamilton Standard "Multi-Application Control System" (MACS) was selected and work commenced to tailor the concept to the Gem to develop the system and to certify it together with the engine Marks to which the system was to be fitted.

6. GEM/HAMILTON STANDARD MACS DESIGN

The system concept is for a control suitable for small turboshaft, turboprop and turbofan engines. A hydromechanical metering unit (HMU) based on (fuel flow/compressor delivery pressure) or ratio units establishes safe operating limits for the engine and allows a "get you home" manual reversion.

This HMU is combined with a pump and filter unit to form a complete hydromechanical fuel control (HFC), driven via the accessory wheelcase, and controlled by the pilot from a single mechanical lever.

Within the radio unit authority limits set by the HMU, and airframe mounted engine electronic control (EEC) (Fig.12) determines the engine fuel flow. The EEC is based on a microcomputer system which calculates the required fuel flow change in response to engine and pilot input signals. The required flow changes are implemented by a stepper motor within the HFC and driven by the EEC computer system. All normal control and limiting functions are achieved in this way. The EEC also includes a free power turbine overspeed protection system which uses a solenoid within the HFC to rapidly reduce engine fuel flow and hence limit overspeed if a main transmission shaft should fail.

The EEC is powered from the aircraft 28V DC supply via 2 essentially independent buses and provides completely automatic control of the Gem engine in flight. The EEC is fully environmentally cleared, including for operation under the high levels of electromagnetic interference, seen in a Naval shipborne environment. For further environmental confidence, the system has been further subjected to simulated lightning strike testing. The heart of the system is clearly the digital computer in the EEC and it is this aspect which will be described further.

A number of inputs from the engine and aircraft are read into the computer under the control of the software resident in programmable read only memory (RPOM). These inputs include :-

- power lever angle sensed within the HMU and representing pilot's engine control demand.

- collective pitch angle, derived from an airframe transducer and and used to obtain isochronous rotor speed governing without control interconnection.

- slope select accessible in the cockpit and used as a basic droop law adjustment for torque matching purposes.

- free power turbine speed select, a basic pilot adjustment of droop law datum via two cockpit controls, one which affects both engines together and the other which differentially adjusts the engines. These inputs are again used to precisely set torque matching.

In addition, engine transducers of free power turbine inlet temperature, high pressure and low pressure spool speeds and free power turbine speed generate primary engine control signals for the EEC computer. Three discrete input signals are also important in determing the control behaviour : "reversion select" which commands changeover from automatic control to manual, "overspeed test" which allows the free power turbine overspeed protection to operate at a reduced datum thereby checking this normally dormant function, and "accessory drive" which effectively disconnects the collective pitch input and allows full checkout of aircraft controls on the ground.

The inputs from the EEC are the phase energisation signals for the stepper motor to produce the required fuel flow modulation, overspeed solenoid drive power and control status signals. A data highway is also available for maintenance diagnostic purposes.

7. CONTROL LAW IMPLEMENTATION

The control laws are all essentially implemented in software. There is an inherent "fit and forget" philosophy - that is, once installed and set up, the system is fully proof against mishandling, provides an excellent standard of control performance and incorporates extensive built in test (BIT) for system self checking. All these features are accomplished by software, which has been rigorously developed to achieve an overall high integrity control.

Gas generator control is based on the use of high pressure spool speed, control of other parameters such as power turbine inlet temperature also being effected through this basic fast acting control loop. Power turbine speed governing is achieved via a droop law of high pressure spool speed versus free power turbine speed, reset by collective pitch angle to produce the overall desired rotor speed characteristic. This technique produces good stability and transient response, good torque matching without the integrity issues of control interconnection and virtually any shape of rotor speed/torque relationship, including higher speed for high torques and characteristics giving higher speeds in the mid power range only. Its one penalty is that it does require initial set-up to achieve torque matching to within $\pm 1\%$: however, the adjustments are designed to facilitate this operation by the pilot.

The control is designed throughout to be compatible with the digital approach : all stabilising filters are implemented digitally and there are logical switching features of the control laws to optimise overall response and stability.

8. CONTROL OPERATION

The operation of the Gem/MACS combination in the WHL Lynx and W30 helicopter produces :-

(a) Fully automatic "hands off" engine starting, with overtemperature protection and governed ground idle. These starts are cool, predictable and consistent. Two gate positions are used, one for normal ambients and another for enriched starts below -10°C.

(b) Full control over rotor speed during the transition into governing, with comprehensive protection against mishandling, overswings and the presence of system faults.

(c) Stable free power turbine governing in all modes of operation - accessory drive, on load and in autorotation. Rotor speed control can be over a range of pilot selectable datum , the available range of settings being determined by the rotor requirements, and the range required to trim out mismatches should a system component become faulty in flight.

(d) Torque matching to better than $\pm$1% over the full twin engine power regime without constraining the rotor speed/torque characteristic in any way.

(e) A good standard of transient control of rotor speed, with limited over and underswings on rapid collective lever movement. This basic control capability enhanced the excellent handling characteristics of the Gem engine.

(f) Comprehensive gas generator protection under all conditions for surge-free accelerations and decelerations, precise limiting and predictable pilot control.

(g) Fast acting free power turbine/rotor overspeed protection.

(h) A manual reversion capability such that in the event of an electronics fault, power modulation is available to the pilot via the cockpit control lever : surge-free engine handling is assured in this mode and free power turbine overspeed protection is retained.

9. HEALTH DIAGNOSTICS

A feature of digital systems considered of great value in its capability of comprehensive checking for system faults. The Gem/MACS software includes extensive BIT for all software inputs employing fault counters to prevent transient out of range signals generating a control problem. The computer can be interrogated via the data highway provided to obtain information on the contents of the random access memory (RAM). Within the RAM there are locations dedicated to fault counters which can be accessed to aid maintenance.

The software BIT in its own right facilitates fault finding in that the failure modes have been configured to provide a high capability of detecting real faults whilst not responding to spurious conditions. Further, the BIT allows continued flight whenever it is safe to do so, which is considered the safest overall approach.

The BIT characteristics are such that where a major fault exists the most appropriate action is taken to safeguard the aircraft (usually this action is to fail-freeze). An ambiguous indication is given to the pilot that a control system fault has occurred and manual reversion is now effective. Where the fault is minor and not readily apparent to the pilot, indication is given post flight for corrective action.

Overall the digital system capability for BIT and data readout is a significant advantage over previous controls in helicopters.

10. DEVELOPMENT AND EXPERIENCE

Close collaboration in the philosophy of the system, together with extensive and encouraging rig and engine test bed development experience, confirmed the confidence level necessary to proceed with the system on an aircraft. The system was thus installed on both engines of Westland company demonstrator aircraft G-LYNX.

The installation was carried out at Rolls-Royce, Patchway, during the Spring of 1982. Close liaison was maintained between Westland and Rolls-Royce at all stages. The installation was completed in approximately two months. Initial ground running and flying took place immediately afterwards, and the full test programme was completed in a further six weeks. The initial flight activity allowed typical development problems, all of a minor nature, to be resolved, and the necessary control characteristics in respect of the aircraft type to be incorporated. Subsequent to this part of the programme the aircraft continued with a 100 hour intensive development flying programme.

The confidence level attained during this period was such that the aircraft continued to fulfill its duties as the company demonstrator.

Total flight time on this particular engine/aircraft combination now stands at over 520 engine hours.

Throughout this period, parallel activities were progressing with engines operating on the test bed to ensure the failure and malfunction characteristics complied fully with the overall failsafe philosophy. An extensive rig and test bed programme was carried out to enable a full understanding of the effect of all failure modes e.g. short circuit, open circuit etc., and to enable the necessary design actions to ensure that the full failsafe philosophy held under all conceivable failure conditions. Also evaluated were the aircraft-associated control system inputs, such as pilot's free turbine speed datum select and trim, collective inputs and other engine parameters, electronic control and pilot control functions.

Following the satisfactory conclusion of this part of the activity, the uprated Gem 60 engines were now installed with digital fuel control systems in the Westland 30 Series 100-60 aircraft. Certification trials on this aircraft are now at an advanced stage.

All models of future production military export aircraft are now secheduled in include this same digital electronic fuel control system.

Total Westland experience of this type of fuel control system now exceeds 700 engine hours.

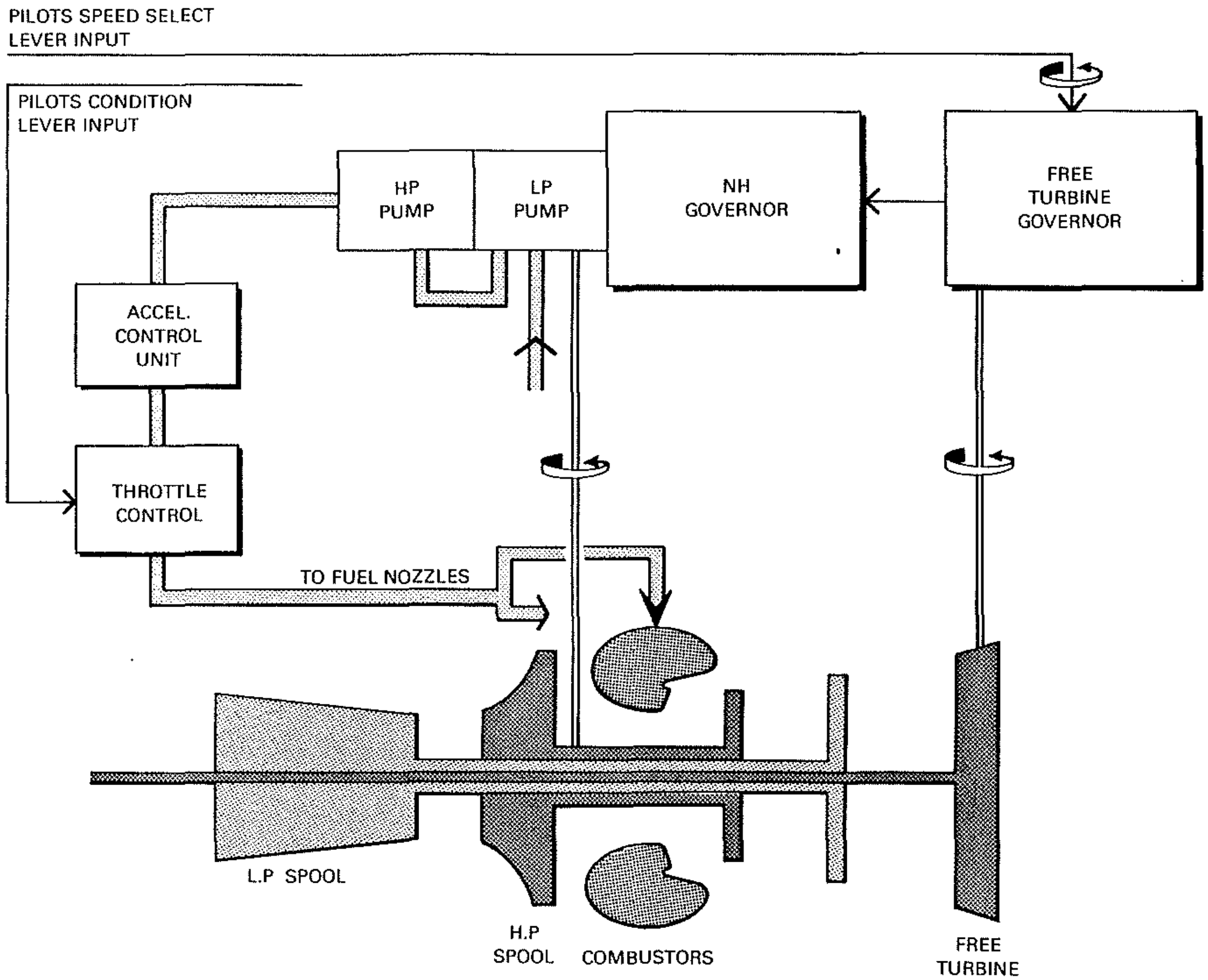

FIGURE 1
TYPICAL HYDROMECHANICAL CONTROL SYSTEM

FIGURE 2 WESTLAND LYNX

FIGURE 3 WESTLAND 30

FIGURE 4 WESTLAND SEA KING

FIGURE 5 WESTLAND WESSEX

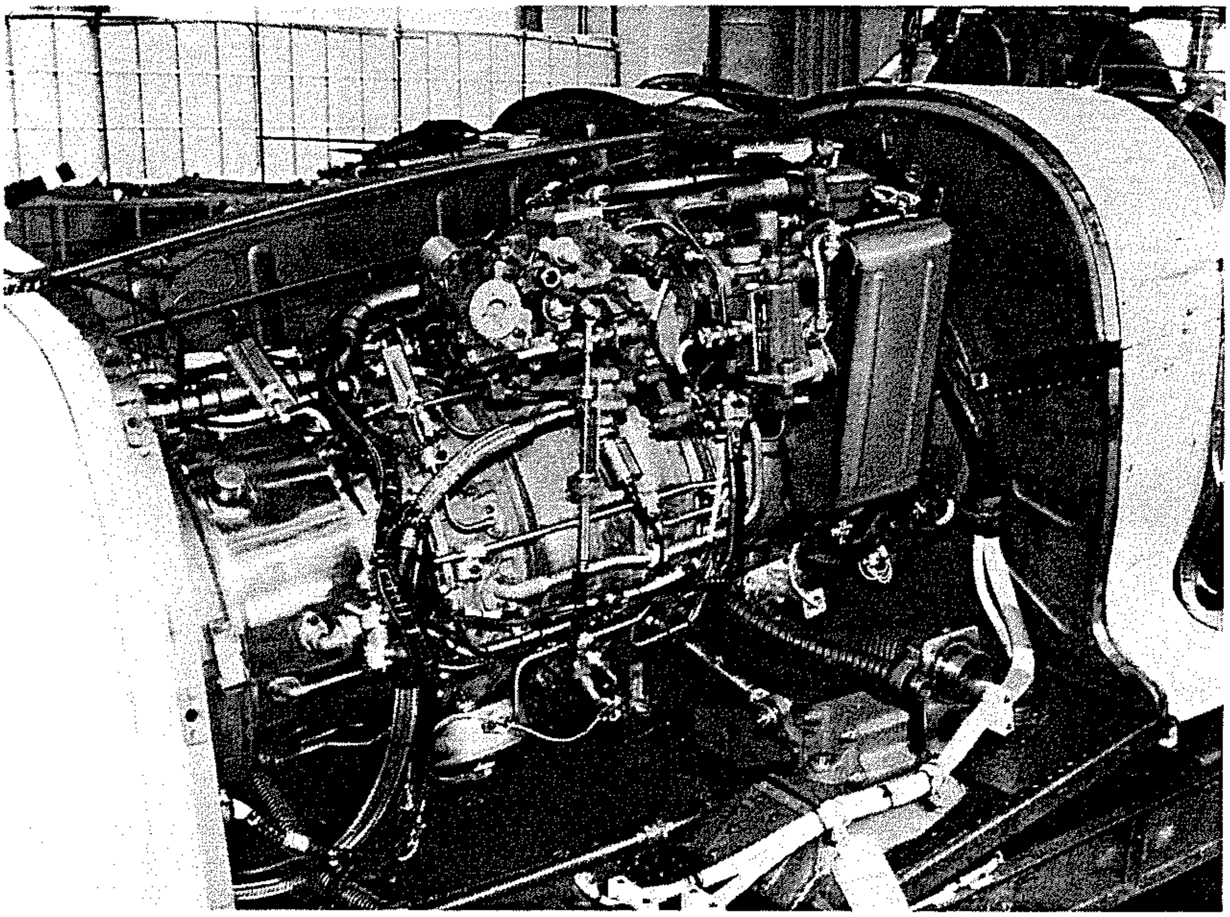

FIGURE 6

WESTLAND 30 ENGINE INSTALLATION

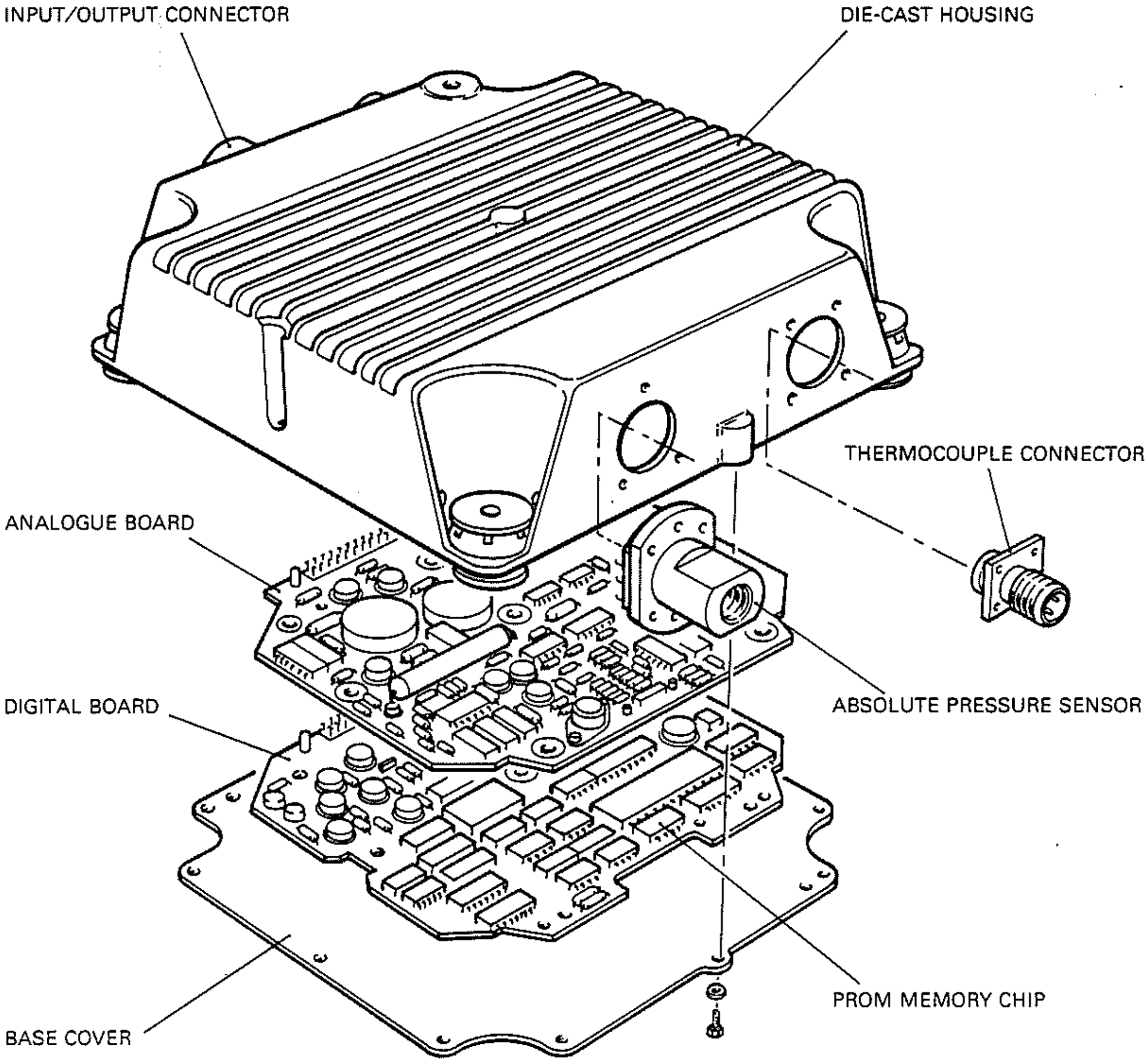

FIGURE 7

ENGINE ELECTRONIC CONTROL CONSTRUCTION

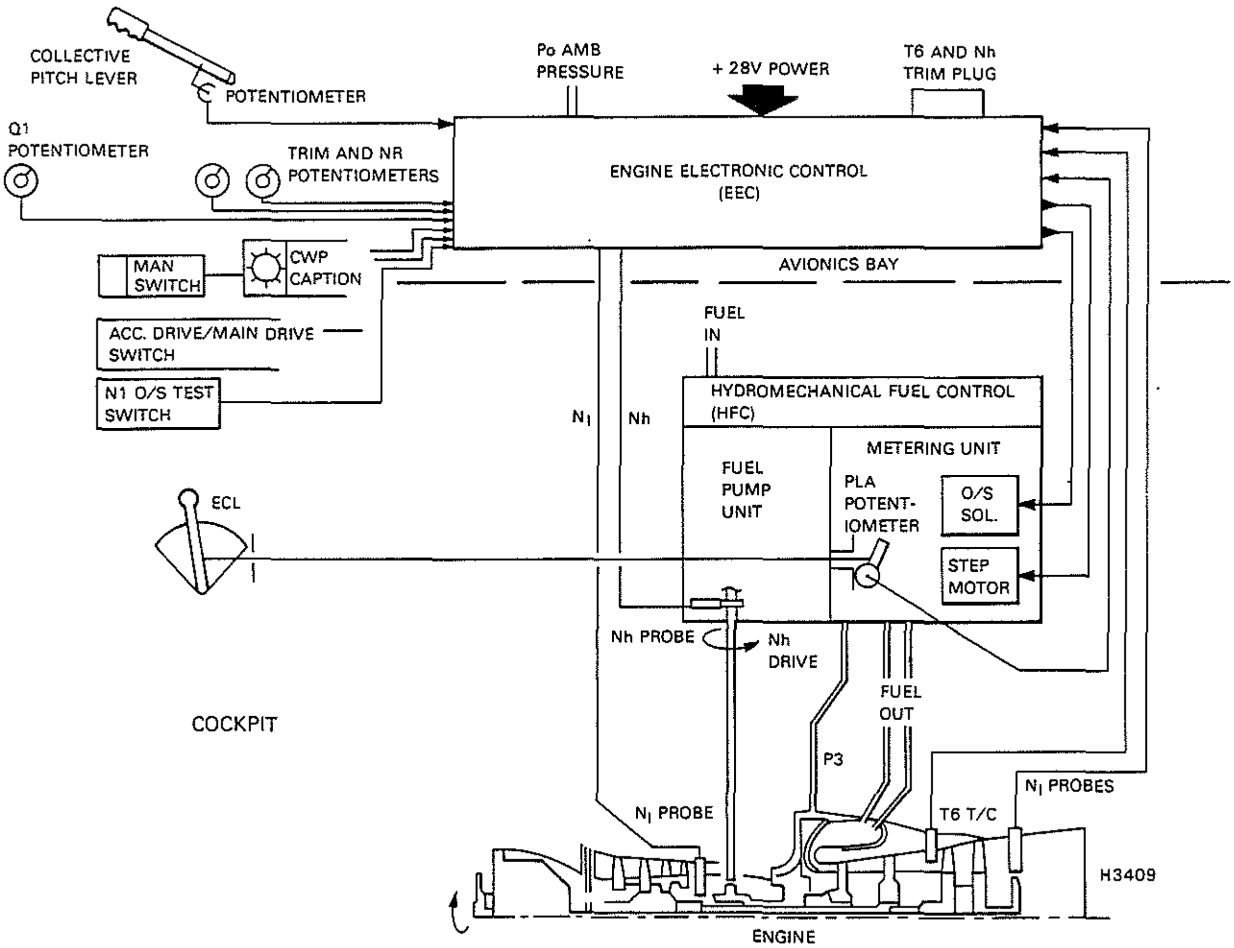

FIGURE 8

HAMILTON STANDARD FUEL CONTROL SYSTEM SCHEMATIC

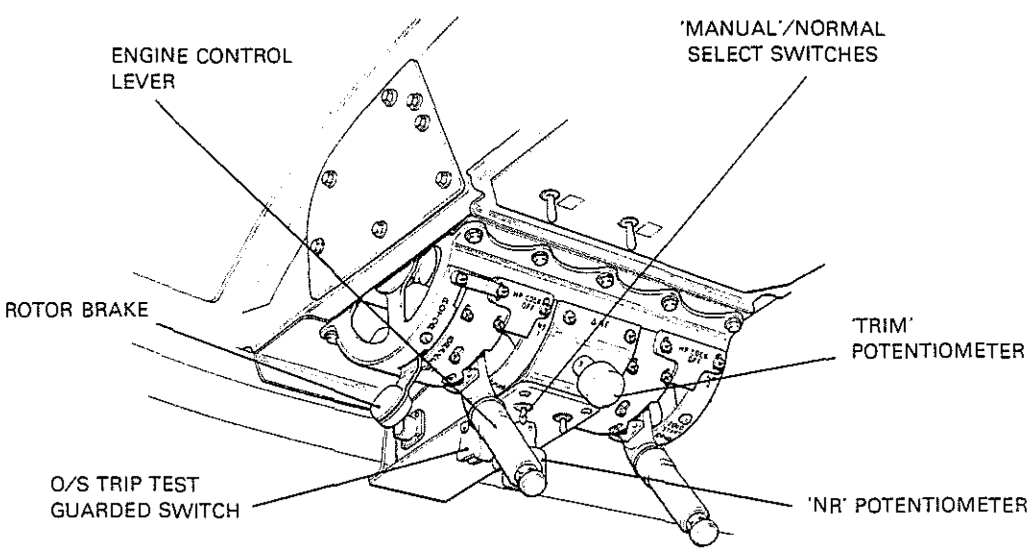

FIGURE 9

WESTLAND 30 SERIES 100-60 ENGINE CONTROL QUADRANT

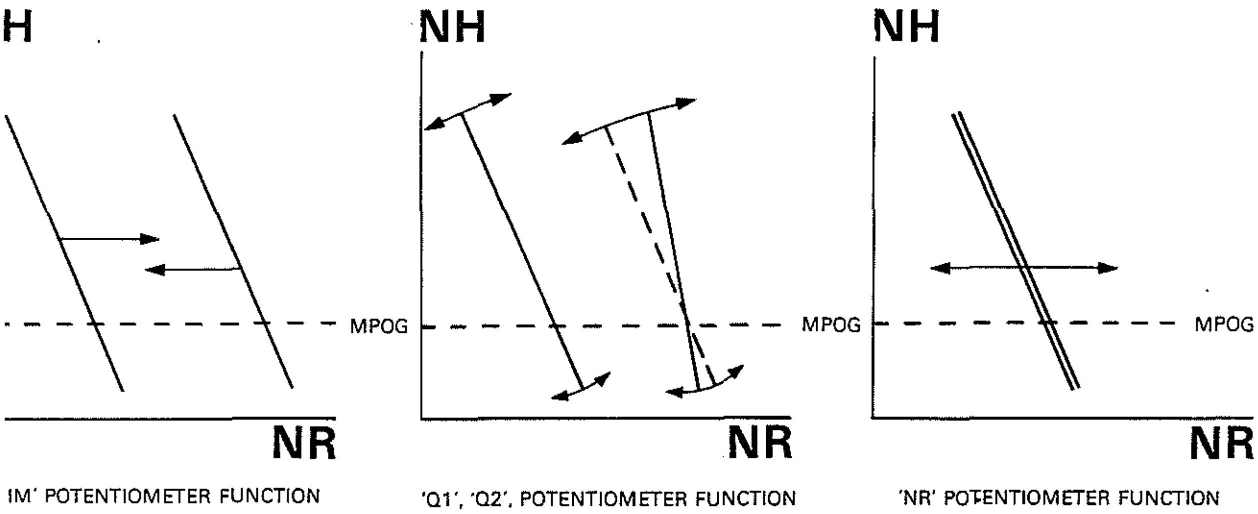

FIGURE 10

DROOP SLOPE ADJUSTMENT

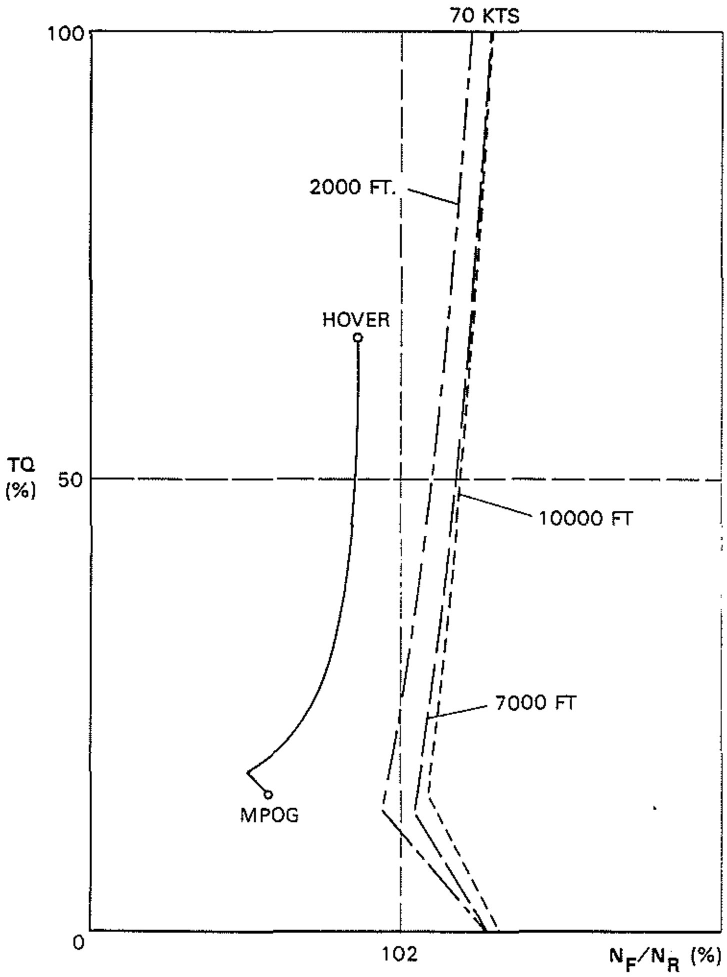

FIGURE 11

WESTLAND 30 ROTOR CHARACTERISTICS

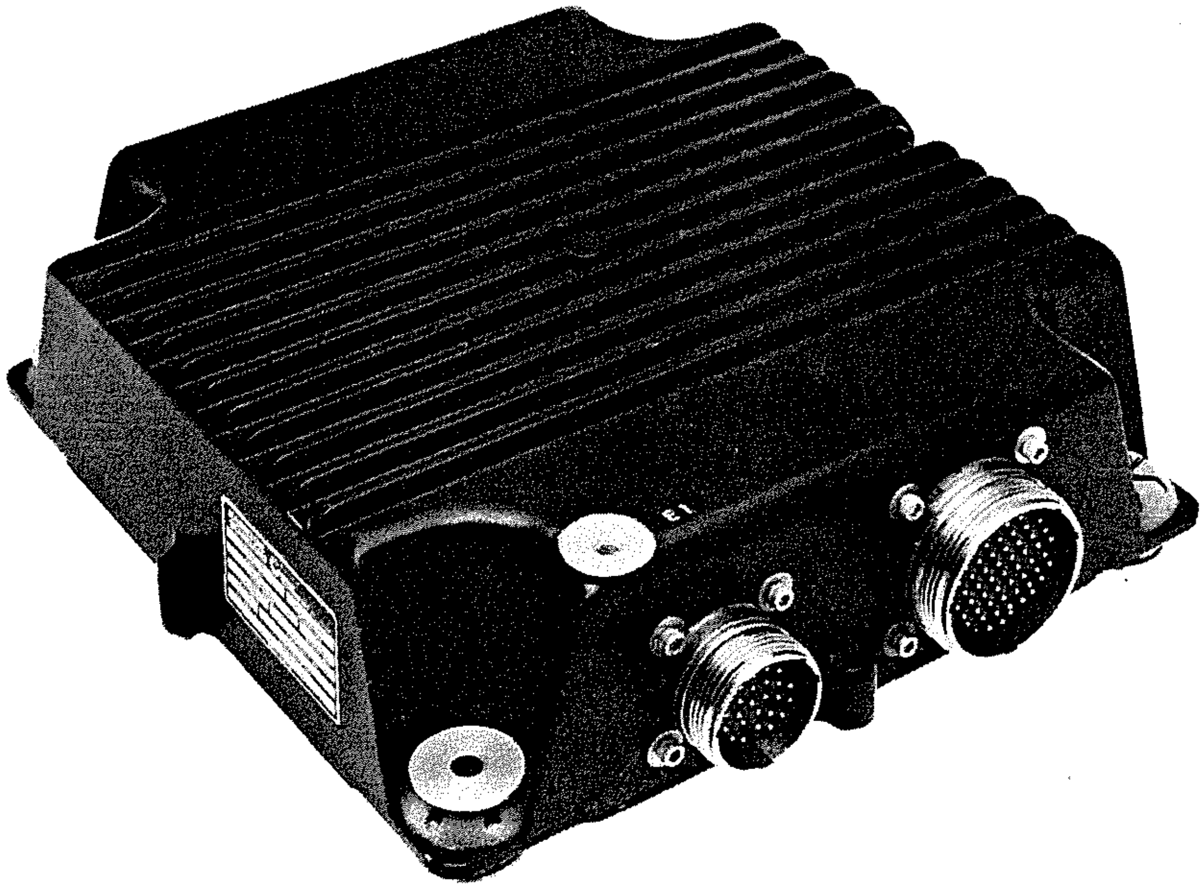

FIGURE 12

ENGINE ELECTRONIC CONTROL UNIT