ENGINE CONTROLS FOR THE 1980s AND 1990s

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Abstract

Experience has shown that full-authority electronic controls have much to offer in both the military and civil fields.

A variety of controls with increased emphasis on minimum hydro-mechanics and use of digital techniques are being developed.

The new systems envisaged can only be exploited to the full with some changes in the way that designs are specified, and if changes in maintenance attitudes are adopted.

The concept of the engine control systems for the 1990s is described with arguments of how integrity, reliability and control system performance will be obtained.

Rolls-Royce Controls Background

Attempts in the USA in the 1950s to introduce electronic controls failed due to the unreliability of thermionic valves.

Rolls-Royce based their controls of the same period on magnetic amplifiers and these were successful.

A full-authority, fly-by-wire, system using magnetic amplifiers entered service on the Proteus Engine in the Britannia Aircraft in 1957. Over thirty million engine hours experience has been accumulated and an engine shut-down rate due to control of 4 in 10^6 hours.

Since 1970 most Rolls-Royce engines have had some form of electronic overspeed and/or over-temperature protection. The more complicated engine arrangements, particularly when combined with reheat and a variable nozzle, have utilised full-authority fly-by-wire electronics. Concorde and military aircraft such as Tornado are in service with these systems.

System Arrangement

The control of each engine without after-burner is based on two channels each of which is totally independent of the other as shown in Figure 1. Input signals are derived from separate transducers and all drive arrangements are electrically duplicated.

Multiple engine aircraft with full-authority engine control do not have any form of mechanical or hydro-mechanical reversion.

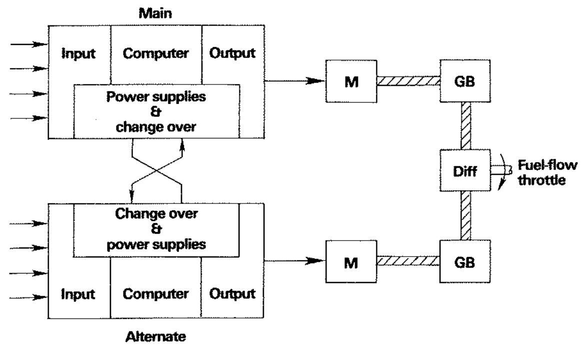


Figure 1. Dry Engine Control

A simple hydro-mechanical or mechanical reversion system is considered desirable with a conventional single engine aircraft and essential with a V/STOL aircraft.

To achieve the integrity requirements for the engine run-away condition, a separate overspeed governor is normally fitted.

Experience with Analogue Controls

The Concorde engine system, illustrated in Figure 2, which has now flown for more than a quarter of a million engine hours, is used as an example.

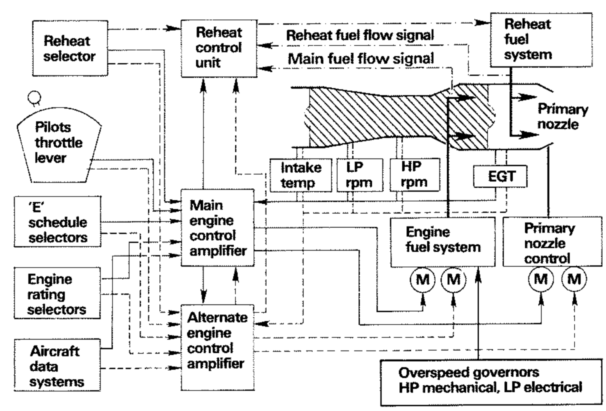
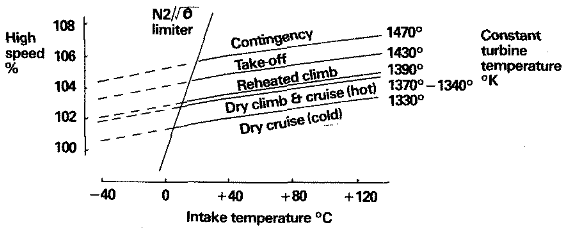


Figure 2. Olympus 593 Mk610-14 Control System Simplified Block Diagram

Experience has shown that the major aspects of control have been met and in many cases improved over conventional hydro-mechanical systems; (ref Figure 3):

- Integrity requirements have been met.
- The overall propulsion efficiency of the engine over a wide range of conditions can be implemented effectively.
- The accuracy and repeatability of the control eliminates throttle stagger.



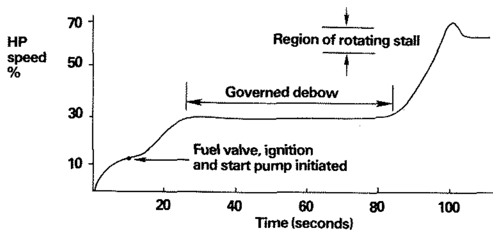
HP speed may be depressed by a 'hot' engine which is exhaust gas temperature (EGT) limited.

The dry cruise characteristic varies with changing ambient temperature.

Figure 3. Olympus 593 Control System HP Speed Limiter (Basic Rating Control) To Limit TET and HP Speed for Selected Ratings

- Automatic starting and in-flight relighting.
- In-flight shut-down rate due to control is compatible with hydro-mechanical systems.

The automatic features, such as starting, together with accuracy and repeatability greatly reduce pilot work-load. (ref Figure 4).



1 Debow selected and start sequence commenced
2 Fuel valve opened at 10–12%. HP fuel pumped by electric start pump
3 Throttle opened progressively as HP speed increases
4 Light-up followed by throttle actuator closing when EGT increase rate (TJ dot) limit exceeded
5 Speed stabilises at 30% to debow HP shaft
6 Debow switched off manually after 1 minute (or immediately if not required)–engine accelerates to 67% HP to clear rotating stall
7 Engine decelerates to idle speed (65%)

Figure 4. Olympus 593 Control System Starting Sequence

The main concern with the Concorde control has been the reliability of the particular elements.

Duplication has maintained the integrity and the reliability has been sufficient not to embarrass the flight operations. However, the maintenance load in response to cockpit warnings etc has been high, and the removal to confirmed defect ratio of control amplifiers has also been high.

Recent introduction of a Fault Identification Module (FIM) using digital techniques has improved the visibility of faults, but has not significantly affected the removal to confirmed defect ratio.

Design Concepts

We are entering the era where the computing power available in micro miniature form will enable a much wider variety of design implementation.

Designs are configured to meet specific target requirements such as:

- Engine run-away 1 in 10^8 to 10^9 hours
- Engine shut-down rate 1 in 10^5 hours
- Mission abort rate 1 in 10^5 hours
- Reliability 3000 hours MTBCD

Designing to achieve these figures does not necessarily leave the customer feeling he has a good system.

It would seem that to fully exploit the new electronics, we should design primarily for minimum customer aggravation, and not simply to meet figures in any particular order.

In obtaining the specification figures, there is a practical time-base that has to be met. For example, integrity requirements such as engine run-away up or down must be fundamental from first flight.

Other requirements, such as reliability, may need to be achieved 12 to 18 months after entry into service.

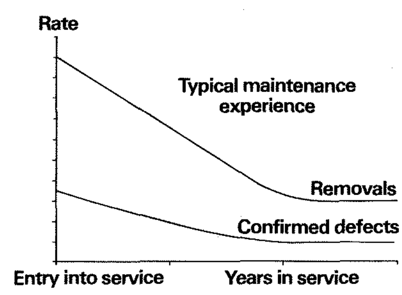


Figure 5. Electronic Analogue Control System

The removal rate and confirmed defect rate are invariably high at the front end of service operation due to the learning curve of Supplier and Operator (ref Figure 5). Much can be done to shorten and reduce the length of this learning curve but the system design should be such that its effect, in terms of customer aggravation, are minimised.

It is Rolls-Royce policy to design

to accommodate X 10 the mature in-service removal rate and still have an effective control system.

The Engine Control for 1985-1995

The engine control advocated for entry into service on Rolls-Royce Engines from 1986 onwards will contain the following main features:

- Minimum hydro-mechanical complexity.
- A duplicated electronic system having full authority for all engine control functions.
- A separate, duplicated overspeed governor.
- The system will be fault tolerant to most component failures.
- The electronics will be engine mounted and probably fuel cooled for subsonic flight applications.
- Maximum use will be made of digital techniques.
- Fault diagnostic techniques will be enhanced by built-in test and fault identification systems.

Basic System

The electronic configuration shown in Figure 6 employs a duplicated lane

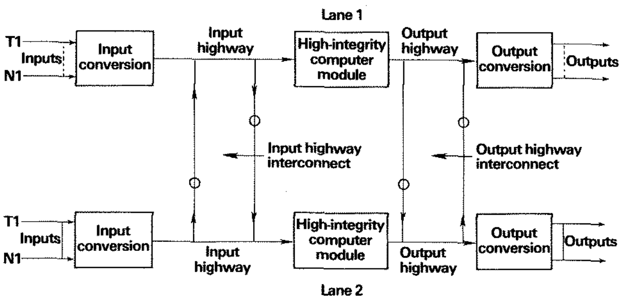


Figure 6. Full-Authority Digital Electronic Control System

with cross-connection of lanes, via a serial or parallel data highway, allowing data flow between inputs and between outputs. The connection around, rather than directly between, the computers, is preferred, as it simplifies procedures in the event of a computer failure.

Each of the computers shown in Figure 6 is a dual microprocessor unit. In the configuration shown in Figure 7, the two

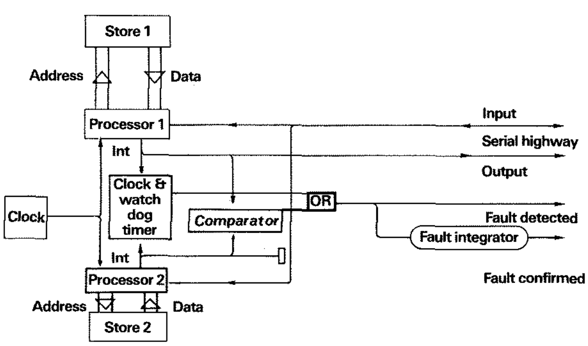


Figure 7. High-integrity Computer Module

microprocessors are synchronised. Output data is compared on a bit-by-bit basis, and if found to be in error a fault is identified and the other lane's high integrity computer module is selected. The main reason for adopting this approach is that we believe this is the best method of ensuring integrity of the computer. The alternative, which is to derive a computer self-test programme, needs extensive testing, and a change to the type of microprocessor means that a new self-test programme has to be produced. The testing required is several man-years of effort.

Fault Tolerance

In the configuration shown in Figure 6, loss of an input (T_1) from Lane 1 opens the input highway interconnect and Lane 1 derives its T_1 input from Lane 2. A second fault on, say, N_1 in Lane 2 opens the input interconnect highway in the opposite direction to maintain a full input data set. Output actuator faults are treated in a similar manner.

In the event of a computer fault, the system will change to use the computer in the alternative lane and all input and output signals will reconfigure.

The interconnect highways utilise Opto-electric couplers of very high reliability and integrity. In the event of loss of communication from lane to lane, the system operates as a duplicated lane without multiple fault tolerance.

There have been four in-flight shut-downs on Concorde, due to control, in the period of 250 000 engine hours. Figure 9 shows the causes.

Double lane failure

1 Amplifier (Lane 1) and actuator (Lane 2)
2 Actuator (Lane 1) and T1 probe (Lane 2)
3 Actuator (Lane 1) and not identified (Lane 2)
4 HP pulse probe (Both Lanes)

Figure 9. Concorde In-flight Shut-downs Due to Control System

Fault tolerance of the type advocated would have avoided any engine shut-down for the first three events.

Event No 4 was a mechanical failure of a gear-box drive and would not have been accommodated. A shut-down rate of 4 in 10^6 hours for control would be most competitive.

Transducer Systems

It is very tempting to put enormous emphasis on the improvement in computing power and how it will improve future systems, but the electronics are only as good as the transducers and connectors that are employed.

Many of the Concorde aggravation problems have been due to intermittent warnings and small pull-offs of rpm or thrust.

The problem has centred particularly on the intake temperature transducer and its associated connector. Motorised actuator reliability has also been suspect, and overall the removal rate of transducers and actuators together has been as high as the electronic boxes.

High Integrity Software

The new and, we believe, critical element is the introduction of software control with digital systems. It is not a good control design which complicates the software unnecessarily to minimise the hardware content.

The complete control system design must be conceived as a balance of hardware and software.

The concept that software can be controlled by detailed conformation to sets of rules is misleading. The rules required are too complex. The concept of testable software is also a fallacy and is not a substitute for visibility.

To obtain certification, the system must be visible to the control engineer, and Certifying Authority in terms of the task the control system is performing, and this gives by far the best protection to all parties.

Therefore, the software personnel must be constrained to a modular form of high-level language that ensures conformality and thus visibility, (ref Figure 8).

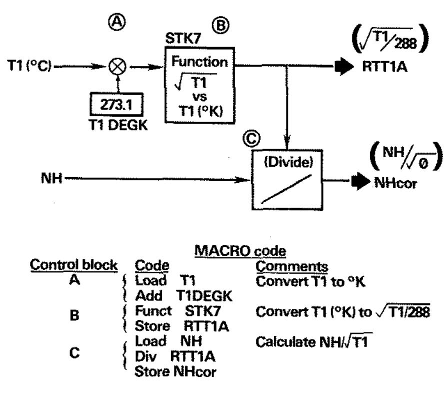


Figure 8. Control Function Conversion to MACRO Instructions

It is absolutely imperative for modification, control and visibility for certification that rules are set and maintained. It is recognised that a penalty is paid in programme run-time to obtain these disciplines. However, with a well organised system, this can be contained to 10 to 15 per cent increase in run-time.

Reliability/Maintainability

Rolls-Royce experience to date has convinced us that most of the benefits claimed for full-authority electronic engine control are available. Moreover, with more complex engines, to reduce fuel burn and give greater automation of the overall aircraft system to reduce pilot work-load, there will be no viable alternative in the 1990s.

The fundamental problem remaining is that of reliability. Integrity can be achieved by redundancy but using more equipment reduces the reliability of the overall system.

To improve the history of unreliability of electronic systems the approach must be combined on several fronts:

- The number of components used in the system must be kept to a minimum.

It is always a great temptation, because the computing power is available, to add features to the system. They may not add to the electronic computation, but they add transducers and connections and other possible fault modes, (ref Figure 10).

- The use of digital, large-scale integration components should improve the reliability of the black boxes.

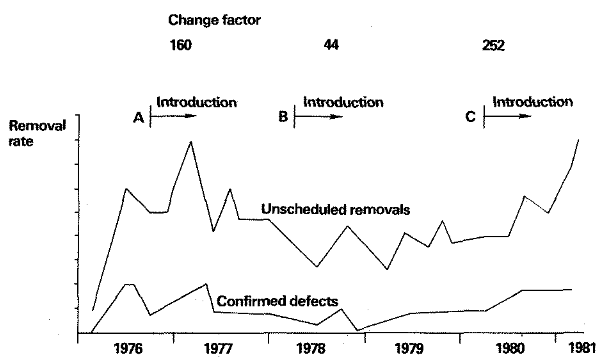


Figure 10. Olympus 593 Control System. ECA Removal Rate Since Entry into Service

Further, it would be expected that the effects of handling the electronic units, to introduce modifications, would be greatly reduced. Modification action would be implemented by using plug-in type store cards, rather than components with soldered connections.

- Reliability programmes at the commencement of any project are essential to reduce the impact of unreliability. Diagnosing any component problems from the beginning, avoids the gradual introduction of changes through production which take a long time to impact on the whole fleet operation.

Fault identification will be offered to the aircraft customer by means of a fault code store. The store can then be interrogated by flight-deck or maintenance crew action. Since we can provide this feature, we should question its use:

1) Should the flight-crew be told and, if they are, can they use the information?
2) In giving the maintenance crew transient information, will we promote more maintenance removals without improving our service operation?

Similarly, with built-in test equipment, care must be taken to ensure that limits are wide, and that small changes which do not impact on the engine operation are ignored by the testing procedures.

Where reliability is difficult to achieve, customer aggravation can be reduced by improving the maintainability of these units and this should be considered when making comparisons with hydro-mechanical systems.

Fault tolerance, as described, opens possibilities of reducing the maintenance load by making use of this feature to carry faults. I would postulate that, with a low probability of a second fault being the same as the first, faults could be carried for 100 hours and probably beyond this figure as experience is built up.

Environment

The environment to which it is subjected will certainly have a large effect on the reliability which can be obtained. Most of Rolls-Royce experience with full-authority electronics has been with the electronics airframe mounted. Engine mounted electronic units have historically been less reliable than airframe mounted units by a factor of 2:1.

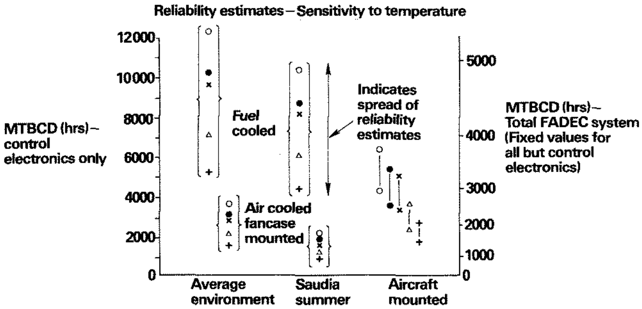


Figure 11. UK FADEC Reliability estimates. Sensitivity to Temperature

It is believed that the engine mounted units can be improved by a factor of 3:1 using fuel cooling techniques.

Figure 11 shows the variation and spread of MTBCD (hours) predicted by a number of suppliers in a number of defined environments on an RB211 engine.

To avoid the necessity to break fuel connections, the electronic units are mounted on fuel-cooled rafts.

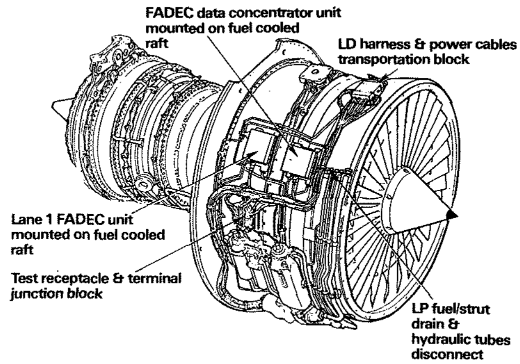


Figure 12. RB211-535C with FADEC system

Figure 12 shows a typical installation.

Conclusions

The entry into service of new, full-authority, fly-by-wire, electronic engine controls in USA civil aircraft is viewed with trepidation in some quarters. The secure feeling of a handle onto the fuel tap is hard to resist.

Electronic controls have been used successfully by Rolls-Royce where the demand, especially in terms of complexity, made the system competitive. In fact, it is probably fair to say that Concorde would never have achieved the engine management requirements, and the interfaces with other engine and airframe systems, without an electronic control.

The need to complicate the engine, in the interests of reduced fuel burn, reduced pilot work load and to integrate the aircraft and engine systems, now brings the new generation of civil aircraft into the same category as military aircraft and Concorde.

Rolls-Royce experience with full-authority analogue systems is in excess of 35 million hours and is increasing rapidly.

The introduction of digital techniques only makes problems we have already solved even easier.

Considerable discipline is needed, when using the new digital techniques, to avoid creating more problems than we solve.

Above all, we must exploit our experience and not plunge too deeply into over-elaborate concepts.

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