Full-Authority Digital Electronic Controls for Civil Aircraft Engines

In the U.K. full-authority digital controls are now being successfully demonstrated on military aero-engines following some years of practical research into suitable configurations for this class of power plant. For the case of Civil aero-engines the appropriate configuration of systems that will enter service from the mid-1980’s has been the subject of much debate between engine/airframe manufacturers and the principal accessory suppliers. This paper discusses the major features that will be embodied in these new systems, particular reference being made to: System tasks and performance requirements; configuration; life cycle costing; electronics design and system interfacing; and reliability and integrity.

INTRODUCTION

The application of full-authority digital engine control (F.A.D.E.C.) systems to Civil Aero-engines is currently at the formulation stage in the U.K., with close dialogue being maintained between Rolls-Royce Ltd., and the accessory suppliers.

The timescale for the F.A.D.E.C. programmes is aimed at starting detailed design during early 1981, and proceeding to certification and entry into service by the mid-1980’s.

The Author’s Company is part of Dowty & Smiths Industries Controls Limited (D.S.I.C.), a grouping created in 1977 to offer a total systems capability in power plant controls. Our combined experience in many years of involvement in electronic controls is reflected in the views expressed in this paper.

Historical Background

Full authority electronic control systems, albeit based on analogue techniques, are not new to the U.K. and many hours of airline service experience have been obtained, firstly with the Proteus Controls in Britannia and more recently with the Olympus controls in the Concorde SST.

These systems represented major milestones in Civil engine controls and valuable operating experience has been gained with their deployment. Although these were designs based on analogue hardware, they well demonstrated the advantages in accuracy and flexibility that electronics has over hydromechanical fuel systems. The hardware necessary for exploiting the programmability and greater accuracy of digitally based systems only became viable with the introduction of fast 16-bit microprocessors in 1976 (Texas SBP 9900 & Ferranti F(JOL)). However, prior to that time, D.S.I.C. had conducted R and D studies on suitable system configurations using hardware based on discrete logic. This led to practical demonstration of the capability of digital controls on the PPS0 engine in 1973 and the Adour engine in 1978. With the availability of suitable microprocessors, further F.A.D.E.C. systems have recently been designed and demonstrated. One is applied to the Pegasus engine in Harrier; the second for Advanced Helicopter engine control studies. Both systems are engine mounted and both configured as dual lane structures with automatic reversion following fault detection.

The results from all the above projects, together with those from other accessory suppliers in the U.K., have demonstrated the power and usefulness of electronics in engine control. The advances in digital electronics technology leading to cheaper and potentially more reliable systems have generated a climate that is now fully receptive to the concept of F.A.D.E.C. systems for civil engines. Reservations remain, however, concerning the reliability and integrity of electronic systems; the present dialogue between accessory suppliers and engine manufacturers has centred largely around these problems.

SYSTEM REQUIREMENTS FOR FULL AUTHORITY SYSTEMS

The basic requirement of a full authority control system is to provide engine control and monitoring over the full range of engine power and aircraft flight envelope.

This broad specification requirement is supplemented by other factors that need to be considered in the design of a practical system. Some of these represent normal engineering problems whilst others are specifically defined by the engine manufacturer:-

1) The system must be capable of interfacing with other aircraft (electronic) systems.

2) The system must accommodate as many defects as possible in the time between stops where


Copies will be available until December 1, 1981.
the flying schedule permits maintenance action.

3) Stringent safety and reliability levels such that the probability of uncontrolled runaway to hazardous overspeed \(10^{-8}/\text{hour}\) or loss of control or thrust \(10^{-4}/\text{hour}\) is no worse than currently attained with conventional hydromechanical system.

4) Cost of ownership to be minimised.

5) Design flexibility such that future expansion or modification for different engine standards can be effected without major redesign.

6) A maximum Built-in Test (B.I.T.) capability to monitor and safeguard against in-flight defects and provide diagnostic features for easier repair.

7) The Electronic Control Unit (E.C.U.) to be engine-mounted and powered from a dedicated engine driven generator.

8) The system to be fully proofed against the usual environmental factors that obtain on an engine. A more recent requirement arising from greater use of composite materials in wing design is the need for protection against lightning strike effect.

9) Provision of simple adjustments for easy trim of certain control features.

10) Simplification of the hydro-mechanical engine interface with attention given to future use of lower grade fuels.

SYSTEM ARCHITECTURES

Basic Configuration

FIG. 1 shows the basic configuration for a F.A.D.E.C. system.

Previous work has shown that a dual inter-connected arrangement offers the optimum solution with regard to safety and cost. Practical operating experience of the configuration has already been gained in the Concorde analogue control system (apart from interchange of data between lanes) and in the F.A.D.E.C. systems previously referred to.

A number of design options are possible with regard to the control lane electronics but all systems will contain a number of essential elements:-

1) A complement of duplicated engine sensor and switch state inputs. In the applications considered e.g. the Rolls-Royce RB211 variants, there will be typically some 12 control parameters, covering shaft speeds \(N_1, N_2, \text{ and } N_3\), pressures \(P_1, P_4, P_{\text{int}}\) and oil pressure), temperatures \(T_1, T_{\text{C.G.T.}}\) and oil temperatures) together with the power demand and feedback signals from the hydromechanical system. A further 10 or so signals are used for engine monitoring purposes and these include further engine temperature and pressure signals, oil and fuel states and vibration conditions. The switch inputs provide additional information on fuel and lubrication systems, thrust reverser mechanisms and other power plant states. On a typical installation there will be between 10 and 15 such signals.

2) Inputs from the Air Data Computer(s) (A.D.C.) and outputs to other aircraft systems via serial data links.

3) A power source comprising a dedicated generator for the control electronics, associated sensors and actuators.

FIG. 1
4) A hydro-mechanical fuel metering control unit and shut-off valve. The fuel flow actuator is duplicated.

5) Inlet Guide Valve (I.G.V.) actuator and solenoids for compressor air bleeds, ignition control, thrust reverser control etc. Dual windings will be provided for integrity.

6) An independent overspeed governor.

7) The E.C.U. which, with present levels of part reliability, must be structured as a multi-lane device to achieve the necessary overall safety targets.

**Electronics Option Studies**

Options for the electronic content of the system include:

1) Lane structure of the E.C.U. with regard to redundancy and inter-lane communication.

2) Amalgamation or not of engine data monitoring functions with control functions.

3) The degree of Built-in-Test and diagnostic facilities provided.

The effect that the above options have on the essential system needs of performance, safety and cost of ownership have been assessed in order to arrive at costed alternative solutions for review with the engine companies.

**E.C.U. Structure**

FIG. 2 shows four control configurations based on a dual lane structure that have been considered in detailed D.S.I.C. studies. In addition to the control configuration shown, further options regarding the inclusion or separation of monitoring functions have been assessed separately.

The dual lane structure is not the only method of attaining the safety targets – lane triplication or higher degrees of redundancy are certainly possible alternatives. Such systems are currently undergoing evaluation as part of current research activities into engine control structures. Because of the higher technical risk that would be involved in their application in the near future, such structures have been excluded from the appraisal.

The configurations shown in FIG. 2, represent four combinations of lane structure:

- **Type 1**: No inter-lane communication, single computer, self-monitored by software checks.
- **Type 2**: No inter-lane communication, duplicated computers with either hardware or software comparison monitoring of outputs.
- **Type 3**: Inter-lane communication, single self-monitored computer.
- **Type 4**: Inter-lane communication, duplicated computers with comparison monitoring.

The Type 1 structure is the simplest hardware arrangement but has two principal disadvantages:

- **a)** Fault detection in the computer section is entirely dependent on self check routines that may not detect a sufficiently high percentage of possible faults to satisfy safety requirements.
- **b)** Tolerance to sensor failures is minimal, any sensor failure apart from a few replicated by the Air Data computer will require a lane change action to revert to full control.

The Type 2 arrangement improves the computer fault detection rate of the C.P.U. by the addition of a second computer. In this scheme the same control program is run on identical input data and the processed data outputs compared. Disparity effects a lane change. System safety has been improved at the expense of reliability and cost of ownership.

The Type 3 configuration corresponds to the Type 1 scheme but with the two sets of sensor data applied to each control computer. This permits a control lane to operate on 'own' data inputs or, in the event of sensor loss, the data from the alternative channel.

The Type 4 structure combines the Type 2 and 3 systems to give a high degree of fault detection coupled with an increased ability to survive sensor or other faults. Clearly, this performance improvement is obtained at the expense of additional hardware and complexity.

The following Table shows a comparison of estimated relative reliabilities, cost of ownership and size and weight for the four options. Also included is the safety aspect which at the time of writing requires further analysis before complete and definitive figures can be released. At the present it is known that Certification authorities favour the Type 2 or 4 solution in which hardware monitoring of the C.P.U. eliminates the uncertainties of software self-check in Type 1 and 3 schemes. This technique is currently employed in the F.A.D.E.C. systems designed by D.S.I.C. for the Helicopter and Pegasus engine programmes mentioned earlier.

**Engine Monitoring Functions**

It is envisaged that additional instrumentation to supplement that required purely for control will be employed in the future for the purpose of improving engine health monitoring. It is reasonable to argue that the computing power available in a F.A.D.E.C. system should be exploited to process these additional inputs and transmit them suitably formatted to a separate diagnostics system via a serial link.

This approach is entirely feasible but suffers drawbacks:

1) In a dual control lane system the monitoring function would need to be duplicated to avoid the inconvenience and hazard of dissimilar lane hardware.

2) The failure rate of the E.C.U. lane would be increased. Steps can be taken in the software to ensure that control lane

<table>
<thead>
<tr>
<th>Type</th>
<th>Relative Cost of Ownership</th>
<th>Relative Reliability</th>
<th>Weight (Kg), per Control Lane</th>
<th>Dimensions (mm)</th>
<th>Safety Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>1</td>
<td>1.14</td>
<td>8.1</td>
<td>(330 x 220) x 115)</td>
<td>?</td>
</tr>
<tr>
<td>Type 2</td>
<td>1.16</td>
<td>0.86</td>
<td>8.9</td>
<td>(330 x 220) x 125</td>
<td>√</td>
</tr>
<tr>
<td>Type 3</td>
<td>0.95</td>
<td>0.82</td>
<td>8.2</td>
<td>2</td>
<td>?</td>
</tr>
<tr>
<td>Type 4</td>
<td>1.03</td>
<td></td>
<td>9.0</td>
<td></td>
<td>?</td>
</tr>
</tbody>
</table>

Downloaded from https://energyresources.asmedigitalcollection.asme.org/GT/proceedings-pdf/GT1981/79641/V004T14A004/2393688/v004t14a004-81-gt-139.pdf by guest on 08 November 2019
performance is unaffected by monitor function errors. Nevertheless, defects to the monitor functions would increase reliability impairment arising from re-work.

3) The integration of control and monitor software would reduce the spare computing capacity of the processor for future control enhancements; it would also make the total software task less manageable.

Table 2 shows the implication of amalgamating the monitor and control functions compared to providing a separate monitor unit.

<table>
<thead>
<tr>
<th>TABLE 2.</th>
<th>Analagamated Control &amp; Monitor</th>
<th>Separated Monitor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Reliability</td>
<td>1.0</td>
<td>1.13</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>21.1</td>
<td>18.9</td>
</tr>
<tr>
<td>Relative Cost of Ownership</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Dimensions (mm)</td>
<td>330 x 220 x 155</td>
<td>330 x 220 x 125</td>
</tr>
</tbody>
</table>

The conclusions of the analysis show that only a small weight penalty accrues with a separate box dedicated to monitoring and that the total cost of ownership is reduced by this approach.

FURTHER DESIGN ASPECTS

The discussion in Section 3 regarding control lane configuration showed that a Type 4 system (duplicated computers and cross-lane communication) is the most complex option likely for a F.A.D.E.C. system. However, the cost of ownership is not drastically worsened by this high integrity option, as Table 1 shows, and it is considered likely that this form of system will be adapted for civil engine applications where safety is of paramount importance.

Irrespective of the system configuration, the F.A.D.E.C. electronics system design poses a number of practical challenges to the designers.

Engine Mounting of Electronics

This requirement allows the engine manufacturer to offer an integrated power plant/accessory package with little or no effect on the design of the airframe. There are some technical advantages over airframe mounting in respect of reduced electrical cable-run and weight and reduced electrical interference. These are offset by the somewhat harsher environment that the electronics must see although with the provision of anti-vibration mounts on the equipment box and location of the unit in the fan case, the environment is well within the capability of electronic components.

Engine mounting of electronics has been practised for over 20 years in the U.K. with fuel or natural cooling employed, depending on the specific application. No new design problems are posed, therefore, by the new requirement. The use of computer aided design in thermal management assessments is now standard and will give some improvement compared to previous empirical methods.

Fig 3 shows a sectional view of the F.A.D.E.C. unit used in the Pegasus system. This particular unit is fuel cooled which entailed some additional mechanical complexity but is typical of the use of high thermal conductance paths between components and case. The use of A.V. mounts attenuates engine 'g' levels by a factor of about 10 in the critical range of engine frequencies. In the fan case region the vibration levels are well below 20g so that the isolated equipment will be subjected to 'g' levels within a 3-5g range. This is easily withstood by the form of packaging shown in Fig. 3 where the printed circuit cards employ cast frames for both thermal conduction and rigid support against vibration. This unit is capable of withstanding over 20g.

Electromagnetic Compatibility (E.M.C.)

The equipment will be designed to meet the requirements of MIL Std. 461 and Boeing D6-16050-2 and equivalent British Standard specifications. Other D.S.I.C. equipments supplied to Rolls-Royce in support of their RB211-524D and -535 engine programmes have met these standards. The major recent change in EMC requirements that is of interest has been the introduction of lightning strike survivability in the Boeing document. Proofing the above-mentioned equipments against the defined lightning strike impulse voltages has not proved difficult and has been accomplished by the introduction of suitable filtering and surge suppression devices on critical input/output lines. These techniques will read directly across to the F.A.D.E.C. system. The Pegasus system of Fig. 3, having been designed for a military application is hardened to conducted and radiated interference levels well beyond those required for civil application.

Built-In Test

Considerable knowledge has already been gained from the development and service operation of full authority electronic analogue controls. These have demonstrated the particular need for accurate and rapid fault diagnosis to minimise delays and maintenance time. In the case of the Concorde system, the diagnostics capability has recently been enhanced by the addition of a dedicated microprocessor fault identification system (I) which stores data on the source of intermittent and permanent failures. This has proved beneficial in reducing the number of unscheduled and erroneous control unit removals as well as generating accurate data on general system health. Intermittent connections in particular resulted in much maintenance activity in locating their source prior to the introduction of a precise means of fault identification.

One of the reasons for specifying digital control systems is that comprehensive fault diagnostics can be provided within the basic controller software structure with a little additional hardware necessary to indicate the health of the system.

The type and format of diagnostic displays to be provided is still the subject of discussion between the engine and airframe companies.

As a minimum, the electronics unit will provide a display that indicates GOOD/OO GO, and FAULT INTERNAL/EXTERNAL (to control electronics) plus a provision for the transmission of fault messages along a serial link to an airframe diagnostics unit.

This BIT facility degrades the electronics reliability by no more than 1-3% and illustrates a useful by-product of digital systems.

Reliability

In support of the general development of digital controls, D.S.I.C. are conducting a programme of rig
and flight testing aimed at demonstrating the reliability of digital systems.

This work currently employs F.A.D.E.C. units from the Pegasus programme but will be extended to include the units for a civil engine application when these become available.

Total rig and flight hours will exceed 100,000 unit hours before the entry into service date in the mid 1980's. This degree of testing is considered essential as a means of attaining the reliability levels demanded.

Testing alone is, of course, not enough to achieve reliability, this is largely determined by the skill of the electronics and mechanical designers in achieving the requisite performance with the simplest structures possible and the employment of the most reliable components.

The D.S.I.C. experience has shown that increased levels of integration in electronics is highly beneficial in increasing system reliability. Our philosophy is thus to minimise part count by maximum use of Silicon l.s.i. and hybrid thin film circuit structures.

Higher levels of integration in addition mean lower power dissipation within the E.C.U. with the attendant reduction in thermal stress.

Custom l.s.i. will be more widely used as a means of reducing part count. The in-house integrated circuit design facilities available to D.S.I.C. have generated many l.s.i. designs for use in power plant and avionic systems. For the Pegasus programme alone, three devices used in signal conditioning, and two for Arinc 429 highway transmission/receive interfacing have been produced.

![Diagram](image-url)

**FIG. 2**

**Choice of Microprocessor and Software Aspects**

The computational demands of a F.A.D.E.C. system are such that only 16-bit microprocessors have been considered for the control function.

The control functions to be performed will include:-

Control of Integrated Engine Pressure Ratio - (IEPR).
. Variable Inlet Guide Valve (VIGV) control.
. Bleed Valve Schedule.
. Acceleration Fuel Control.
. Deceleration Fuel Control.
. Starting Operation.

Our studies at this stage conclude that the above functions can be performed by established micro-processors of the SBP 9900 type but with little margin for future expansion. Table 3 shows a sample mix of routine usage used in scaling input variables, executing control laws and driving a stepper motor, based on the Texas SBP 9900 processor.

Table 3

<table>
<thead>
<tr>
<th>Routine</th>
<th>Usage/Iteration Cycle</th>
<th>Run Time (mS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Carpet Look-up</td>
<td>15</td>
<td>15.1</td>
</tr>
<tr>
<td>2. Table Look-up</td>
<td>12</td>
<td>4.9</td>
</tr>
<tr>
<td>3. Lag/Lead Filter</td>
<td>5</td>
<td>3.8</td>
</tr>
<tr>
<td>4. Multiply</td>
<td>21</td>
<td>2.2</td>
</tr>
<tr>
<td>5. Divide</td>
<td>4</td>
<td>0.5</td>
</tr>
<tr>
<td>6. Output Drive</td>
<td>20</td>
<td>1.6</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>28.1</strong></td>
</tr>
</tbody>
</table>

Note that the above routines do not represent the full computational load on the processor. The options that remain open for a satisfactory solution are open:

- a) The choice of a faster processor but for which little operational background exists.
- b) Increased iteration time, with risk of lowered closed loop stability margins.
- c) More complex software structures to schedule computations in which slowly varying parameters are sampled and processed less frequently.

CONCLUSIONS

The paper has attempted to present a U.K. supplier's view of the options and problems currently being considered for a F.A.D.E.C. design together with some background experience that will be employed in its realization.

The technology and know-how gained from past and current programmes are such that a rapid transition to electronic control can now be made.

ACKNOWLEDGMENTS

The Authors wish to thank the Directors of Dowty & Smith's Industries Controls for permission to publish this paper. They also express their appreciation of the many Engineers at Ultra Electronic Controls Ltd., and Smith's Aviation who have contributed much of the background material.

REFERENCES