DISCUSSION

G. KRISHNAPPA

Did you try to determine degradation in the performance of the aerodynamic components using vibration analysis?

Author's Reply:

We never use the vibration analysis as a diagnostic tool for the compressor or fan efficiencies. But in development one can relate some engine vibration levels to the aerodynamic disturbances as approaching surge.

J. HOUILLON

Quelle est la corrélation entre les défauts constatés par diagnostic et ceux réellement constatés par le réparateur? Pouvez-vous donner le pourcentage de réussite rencontré dans la R.A.F. et plus particulièrement sur un moteur technologiquement très complexe tel que le moteur à trois axes RB 211.

Author's Reply:

I show you the slide (fig 5 of my paper) where I indicate the number of signatures taken, and the success rate of these analyses. Even if the RB211 is a three spool engine, it does not suffer much vibration problems. As shown on fig 5, on 13 tests there was one rejected engine which was indeed due to a HP turbine blade.

H. AHRENDT

1. Do you derive your spectrum information from one specific engine running point or does it cover the whole speed range?
2. Did you derive your information about malfunctions of internal components (i.e. oil squeeze bearings) by external mounted pick-ups?
3. Can you relate malfunction signature of a specific engine-aircraft configuration to a different one as a new engine on a new aircraft?

Author's Reply:

1. The spectrum looks over the whole speed range, idle to maximum, and is derived through a continuous acceleration taking 1 to 1½ min.
2. We can derive them from external pick-ups but it is not the best method. A very good way is to monitor the oil pressure in the supply line of the bearing.
3. The out of balance excited responses generate specific bands of vibration which vary with the engine type, because they are related to the design and dynamic characteristics of that structure. The combination of engine and airframe or engine and test bed produce these unique characteristics.

FAULT MANAGEMENT
IN AIRCRAFT POWER PLANT CONTROLS

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INTRODUCTION

The advent of Digital Electronics in aviation has opened new doors to fault management as a tool to enhance aircraft operability and safety of flight. Today it is possible to integrate flight control systems with power plant management systems. Operability of a battle damaged aircraft can be enhanced under certain conditions through sophisticated fault management systems.

This paper reviews some of the considerations applicable to engine control fault management systems in commercial aviation. Engine control systems have evolved inthe last decade from being primarily hydromechanical to being primarily electronics. This rapid growth in acceptance of the electronic systems by the aviation industry was due to the improvement in reliability of the digital systemsover analogue systems, which were previously in use.

The fault management system is a powerful tool to organize and optimize the maintenance logistics. Operating costs can be significantly reduced with an appropriate fault management system on board.

The paper presents:

- A Brief Review of the Evolution of Engine Controls.
- The Emergence of Fault Management Systems (as part of Engine Control Systems)
- Maturity of Fault Management Systems (Still in Evolution).
- Future Potential.

EVOLUTIVE PROCESS

The fault management in hydro-mechanical controls is simple in concept and difficult in implementation compared to its counterpart microprocessor based digital electronics with their massive memory and computing capability.

The perceived high reliability of the mechanical components drove some engineers to design their control systems without back-up or independent protections and accepting an engine out (or a loss in power) in the case of an engine control failure.

Hydro-mechanical controls have a major handicap, they do not detect failures. Due to this, the concept was to surround the control system with autonomous devices that will prevent critical parameters from being exceeded (example: overspeed protection). Also, these control systems are unable of deciding if they still are in condition to control the engine. If a back-up control exist the system relies on the pilot to diagnose the failure and transfer to the back up control.

The engine control industry could not stay indifferent to the "invasion" of electronics. Analog circuits started to be used in instrumentation and ancillary functions. As engineers became satisfied with the reliability of these electrical components they started to expand their utilization to the main control. As a result, analog controllers started to be used as supervisory units with limited authority or as protective systems and later stepped up to full authority control, with its pinnacle on the"Concorde" Twin channel application. These systems having limited fault detection restricted to checks on voltage thresholds and still rely heavily on pilot detection and action.

The last decade has witnessed a giant leap forward in control concepts. Makin use of the digital technology and microprocessors, the control laws became more elaborate and the fault detection, isolation and accommodation, which constitutes the fault management was called to play a major role.

Fault detection on todays Full Authority Digital Electronic Controls (FADEC) is extensive. Levels of fault coverage range from 80 to 100%. Levels on the hig 90 are possible with internal checks. However, fault coverage of the remainin (up to 100%) can not be achieved internally. The most common configuration to achieve this level is the voting agreement between two out of three control channels to isolate the faulty controller.

The microprocessor based digital control system gives to the engineer extensive power with which to configure the control system to optimize fault management. Controls that use internal checks as a mean of fault detection have two possible philosophies when it comes to fault accommodation. One of the philosophies advocates that cross talk between the channels should be reduced to its minimum and that when a fault is detected the channel in control should give up control, transferring the control to an identical second channel. The other approach defends that the channel in control should remain in control fo as long as it can before transferring to a second channel. To sustain control after a fault, the channel in control has to borrow parameter inputs from the second channel (if it lost its own).

This second approach increases substantially the cross talk between channels and the complexity of the software.

AIRFRAME INTEGRATION

There has always been a degree of integration of the power plant control with the airframe. Its complexity, as expected rises with the number of engines. O single engine aircraft the interaction is limited to the aircraft and the engine control. However in the case of a multi-engine application interactions exist between the engine and the airframe as well as between engines.

The functions that have a degree of interaction between two (or more) engines need to be restricted to a very limited authority such that a failure on one engine does not have detrimental effects on the other engine(s). Typical examples are syncrophasing (on Turboprops), Torque matching (Helicopters), etc.

Mechanical controls often have a reduced number of parameters interacting with the airframe. Usually, these parameters are confined to control requirements and minimal if any are dedicated to fault annunciation. Mostly, fault analysi relies on the pilot report and subsequent interpretation of it by the maintenance crew and available troubleshooting charts.

Microprocessor based digital controls have demonstrated their potential for fault management and for information transfer to the maintenance crew. The transfer of information between the control and the maintenance crew can be done in many different ways. They start with simple interrogation devices which are connectable to the Engine Electronic Control (EEC) unit allowing the crew to read the memory locations where the fault identification is stored. I the more sophisticated applications the EECs are linked with the aircraft EICAS-Engine Indication and Crew Alerting System and/or a Central Maintenance Computer (CMC). Using a serial data bus the fault information is downloaded t these aircraft computers. The maintenance or flight crew can then interrogate the CMC with the faults being displayed in plain language through multi-function displays.

In recent years there has been increasing demand for the implementation of systems that are able to detect and identify failures not only internal to the EEC but also external. External failure can be detected to the level of Line Replacement Units (LRU) associated with the EEC (i.e. input sensors and output effectors) as well as other power plant LRU's.

Potentially, a well designed fault management system improves not only the maintainability of the control system but also reduces pilot workload and extends the life of the engine. With FADEC controls it is becoming common place to configure systems which enable aircraft take offs with the engines producing 90% of the maximum takeoff power capability. In the case of a detected power plant failure the remaining engine is automatically commanded b its EEC to raise its power to 100%. This take off configuration extends substantially the life of the engines but it requires a health status of the opposite engine to be acknowledged by the local engine control. Failures that are immediately identified and automatically accommodated result in a significant reduction in pilot workload compared to that required in fault handling using hydro-mechanical controls.

CERTIFICATION REQUIREMENTS

For all practical purposes the various civil certification regulations are not significantly different with respect to power plant controls.

As an example the certification requirements imposed on an Engine Control System are part of the following FAA regulations:

FAR 33
FAR 25
FAR 27
FAR 29
TSO C77a

If integration of the propeller and engine control is considered then FAR 35 requirements have to be considered.

The purpose of this section is not to give a detailed description of certification requirements and procedures but to highlight what is considered to be the main impact of certification requirements on the hardware and software Fault Management Configuration.

For the purposes of this discussion we will consider FAR 33 that addresses the engine certification as such and FAR 25 that addresses a transport category airframe certification. An Engine Control System that complies with these requirements is basically certifiable to FAR 27 and 29 for helicopters or TSO C77a for APU's.

Given the trend towards greater integration of airframe systems the airframe certification has an impact on the Engine Control System configuration.

The advent of such functions like engine-to-engine synchronization, Automatic Takeoff Thrust Control System (ATTCS), Autofeather etc increases the complexity of the Engine Control System and their certifiability is one of the important drivers for the hardware and software configuration.

Some typical requirements that are specified for a twin engine commercial aircraft Engine Control System are:

a) Unprotected overspeed (O/S) of the engines rotors must be extremely improbable (<1 failure per 10^9 hours).

b) Dual engine in flight shutdown (IFSD) must be extremely improbable (<1 failure per 10^9 hours).

c) Single engine IFSD shall be improbable (<1 failure per 10^5 hours).

d) Loss of thrust of one engine in the takeoff phase and failure to uptrim the other engine must be extremely improbable (<1 failure per 10^9 hours).

e) Complete inability to shut the engine down must be extremely remote (<1 failure per 10^7 hours).

f) Faults in either the Engine Control System or the Airframe Instrumentation System resulting in hazardous operation of the other system must be extremely remote (<1 failure per 10^7 hours).

If the Engine Control System also includes an integrated propeller control, the additional set of requirements that are typically specified are:

a) Unprotected overspeed of the propeller must be extremely improbable (<1 failure per 10^9 hours).

b) Unwanted travel of the propeller blade pitch to a position below the normal flight low pitch stop must be extremely improbable (<1 failure per 10^9 hours).

c) Unwanted travel of the propeller blade pitch to a position higher than the maximum angle of attach causing blade stalling must be improbable (<1 failure per 10^5 hours - similar to single engine IFSD).

d) Complete inability to feather the propeller blades must be improbable (<1 failure per 10^5 hours).

OPERATIONAL REQUIREMENTS

Typical operational requirements specified for a commercial aircraft Engine Control System are:

a) Probability of the inability to dispatch <1 failure per 10^4 hours.

b) Built-In-Test-Equipment (BITE) functional test capability in the maintenance mode to test more than 95% of the system's components/LRUs.

c) Scheduled maintenance for possible dormant faults at time intervals greater than 500 hrs.

FAULT MANAGEMENT CONFIGURATION

To meet the Safety and Certification requirements and the operational requirements both aspects of the configuration hardware and software are equally important and in many cases trade offs between them can be made.

The Fault Management Configuration discussion will center on a FADEC System since these systems have become more common.

FADEC is a system where the processor based digital electronics have full authority on the effectors (without mechanical constraints), therefore being able to drive the engine from low to maximum limits.

A typical FADEC system comprises the following (see also figure 1):

- Input sensors (engine parameters and feedbacks).
- Engine Electronic Control (EEC) unit with input interfaces, processing hardware and output drivers.
- Effectors

The Engine Electronic Control (EEC) unit processes all the signals from various engine and airframe sensors and controls a fuel flow motor in the Hydromechanical Unit (HMU), one or two variable geometry motors and various solenoids and relays. Modern FADEC Systems are Fly-By-Wire (FBW) systems where all signal acquisition (including the pilot command signals) and effectors control are done through electrical links.

HARDWARE CONFIGURATION RESULTING FROM CERTIFICATION REQUIREMENTS

The hydromechanical part of a FADEC system can be substantially simplified because all the computations, altitude, temperature compensations etc are implemented in Software based algorithms and tables.

The simplicity of the hydromechanical part makes it very reliable with an IFSD rate of typically 3 to 4 x 10^{-6}/hr.

This allows for an IFSD rate of 6 to 7 x 10^{-6}/hr for the electrical part of the system to achieve the single IFSD Certification requirement.

The failure rate of the electrical/electronic part of a FADEC channel generally falls in the 150 x 10^{-6}/hr range. For 70% of this failure rate i.e. 100 x 10^{-6}/hr (CPU, drivers, effectors etc), there is no possible accommodation within the channel.

This points to a major configuration impact: with today's electronics reliability, a FADEC system has to have at least a dual independent channel configuration for its electrical/electronics part (See Fig. 2). In fact, a dual channel FADEC system has a significantly lower IFSD rate than a complex hydromechanical system.

<u>If it is assumed that all faults are detected</u>, the IFSD rate of such a system will be:

$$\lambda_{\text{IFSD}}^{\text{Hydromechanics}} + \lambda_{\text{IFSD}}^{\text{Electronics}\ 2} = 4 \times 10^{-6} + (100 \times 10^{-6})^2$$

$$= 4 \times 10^{-6} + 1 \times 10^{-8} = 4 \times 10^{-6}/\text{Hr.}$$

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