THE M53 TURBOFAN CONTROL SYSTEM : A STRONG BASIS FOR THE DEVELOPMENT OF FUTURE DIGITAL CONTROL SYSTEMS

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The main concepts of new engine controls have already been introduced by SNECMA in the control system of the M53 turbofan. Detailed examples will be given to demonstrate that the concepts of full authority, redundancy, failure detection, reconfiguration and software reliability have been tackled with the development of a digital control computer on the P2 version of the M53 engine. This computer performed very successfully, associated with hydromechanical controls permitting efficient reconfiguration when required. Therefore, the M53 engine control system will provide SNECMA with a strong starting basis for the development of future digital control systems.

Introduction

The purpose of the control system of an engine is to control its operation in response to the pilot's order. Because of the increasing complexity of functions requested from the control system, the fully hydromechanical technoloty was progressively replaced by electro-hydraulic systems. The role of the electronics was confined first to a limited trimming of the hydromechanical functions. Subsequently, this role was extended to full authority control (therefore, over the full range of action) of hydromechanical components in order to make full profit of the improved accuracy brought forward by Electronics.

Now, this analog electronics is giving the way to digital techniques : advanced engine control systems are using one or several digital computers.

Why digital controls ?

This evolution can be explained by the combination of two important factors :

- the ever increasing number of functions required from aircraft engine control systems in order to improve the performance in terms of higher thrust, faster transients, lower fuel consumption, operation closer to limiting values, aircraft/pilot dialogue etc,
- the considerable computation capacity brought forward by digital techniques and microprocessors within a constantly shrinking physical volume.

The introduction of digital control systems is a major step forward obliging all engine control system designers to change their design and development concepts to take account of new techniques to be mastered.

Note in passing that the same applies to aircraft controls such as fly - by - wire or navigation systems.

The FADEC or RENPAR types of control systems involve the application of new concepts which are becoming known better and better :

- Full authority control through a digital computer.
- Redundancy.
- Failure detection and identification.
- Failure tolerance.
- Software safety.
- Reconfiguration.
- Assistance to maintenance.

These concepts have already been partly introduced by SNECMA in the M53 turbofan control system currently produced and in service with the MIRAGE 2000 aircraft. Without getting into a detailed description of the M53 control system, I would like to present some specific examples which will demonstrate that most of these new concepts are already introduced in this control system.

The M53 turbofan and its control system

The M53 turfofan is a military engine delivering a maximum augmented thrust of 9 500 daN ; this is a single shaft turbofan design, with afterburning on both flows.

The main functions controlled by the control system are :

- Dry fuel flowrate.
- Exhaust nozzle area.
- Fan flow regulator area.
- Core engine AB burner ring fuel flowrate.
- Fan duct AB burner ring fuel flowrate.
- Emergency fuel flowrate.

On top of this, other ancillary functions must be considered, e.g. the ignition system, engine shut off valve, cockpit display, warning signals etc.

The block diagram of figure 1 shows the major components of the M53 engine control system :

- a main fuel control unit,
- an afterburner fuel control unit,
- a computer controlling the above two control units,
- a backup control, independent from the above accessories,
- the various pumps required,
- injection and flowpath variable geometry components.

Let's recall here that the MIRAGE 2000 is a single-engine aircraft, which explains the backup system.

Full authority

All controls are such that the electronics has full authority on the actuators over their full range of action :

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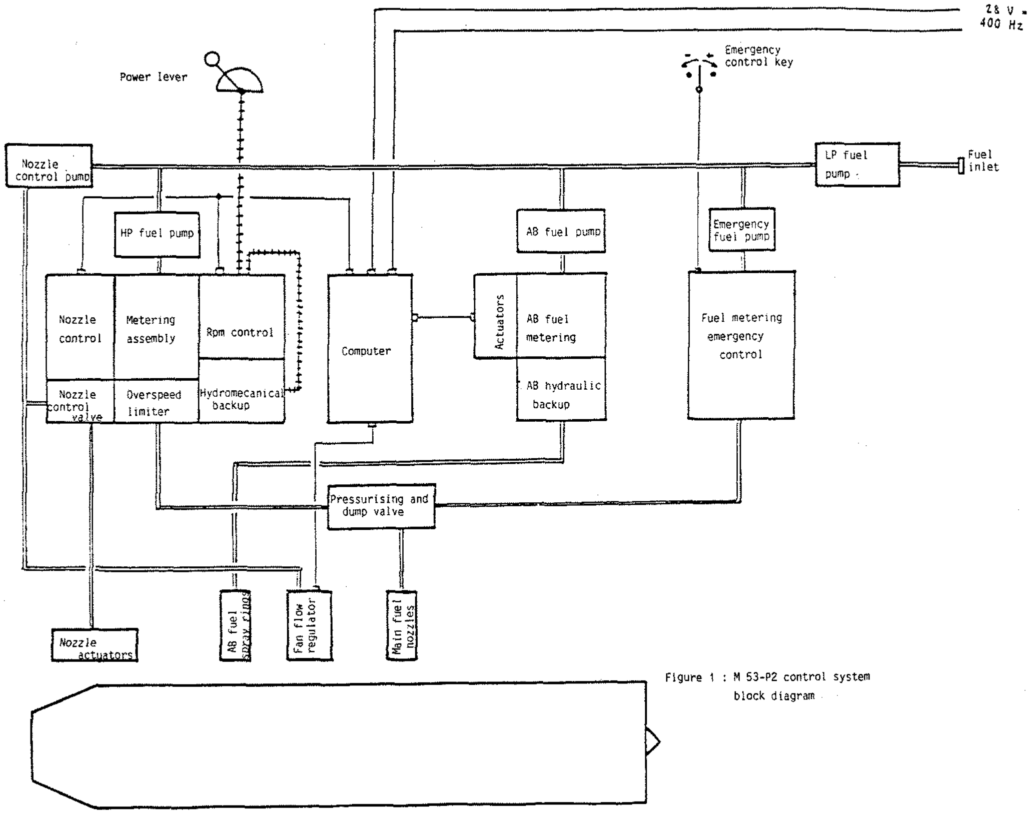

Figure 1 : M 53-P2 control system block diagram

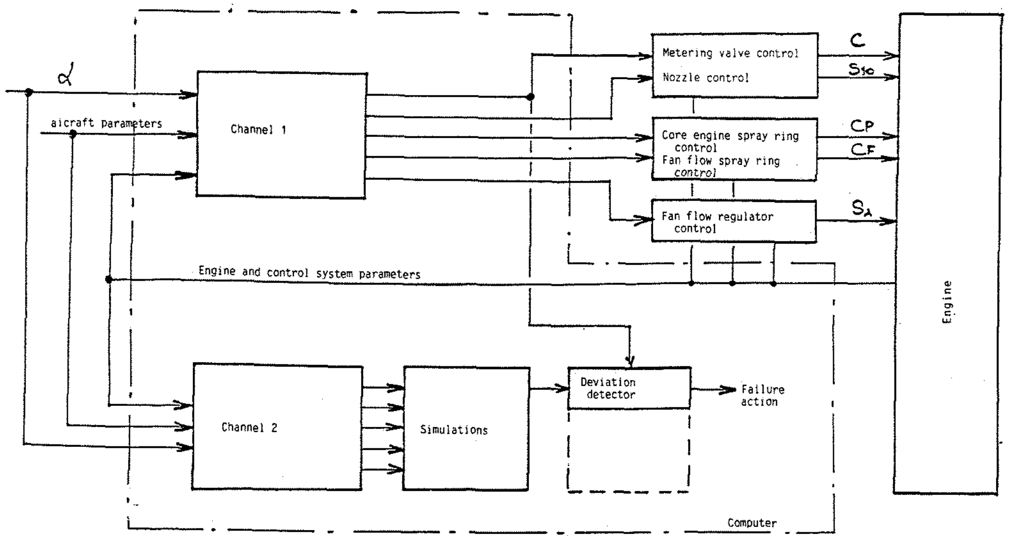

Figure 2 : Dual computer architecture

- Either trough a force balance (dry engine fuel metering valve and nozzle area control).
- Or direct (AB fuel metering valves and fan flow regulator).

With full authority control, the quality of sensors and the adaptation of correction networks allow to take advantage of the accuracy and transient response optimization offered by Electronics over the full range of action of the controlled component.

On the other hand, with a full authority control, the operation of electronic systems must be carefully monitored, as any single failure of an electronic component, may cause a catastrophic failure, e.g. the control of a metering valve running fully open or fully closed.

The use of the full authority concept must be associated to efficient monitoring and test means. The M53 control computer incorporates such failure detection features.

The electronic computer

The electronic computer controls the engine operation through the dry and AB hyromechanical fuel control units and the variable fan flow regulator adpating the bypass ratio. For this purpose, signals from a set of sensors are applied to the computer. These sensors are duplicated to avoid the loss of control functions using these signals, in case of failure of one sensor.

Figure 2 shows that the computer comprises two identical computation channels :

- An active channel, controlling the electrohydraulic components of control units.
- A reference channel, controlling an electronic simulation of electro-hydraulic components.

From the permanent comparison of the actions of both channels, any failure affecting either channel can be detected and the computer can be deemed out-of-order. In this case, the control system is reconfigured to a fully hyromechanical system.

In a first version, the 53 computer was an analog system. As early as March 1983, simultaneously with the development of the M53-P2, a digital computer was designed to be dully interchangeable with the analog computer.
This change provided two advantages :

- More functions could be integrated in a same box volume.
- The control schedules could be developed more rapidly, since, with a digital computer, the introduction of changes is much more straightforward.

This step forward was a major success, materialized in December 1984 by a trouble-free first flight. This was the opportunity to acquire a preliminary experience in the design of engine-mounted digital computers.

A specific aspect is worth being mentioned : the hardware/software organization selected by SNECMA for its digital control computers.

For us, a digital computer comprises :

- a programmable component comprising the hardware and the associated software,
- an application software generating the selected control schedules.

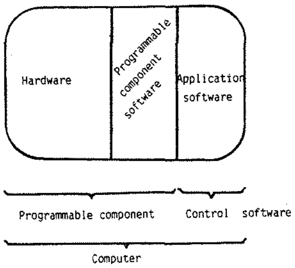

Figure 3 : Schematic arrangement of a digital computer

With such a arrangement, the application software, which is often changed during the development of the engine and its control system, is kept independent from the hardware by means of an intermediate programmable component software.

The control software is designed by a team of engine control experts. On the order hand, the programmable component software is designed by a team of experts in electronics. Both teams work in close cooperation and, through their complementarity, towards producing digital computers fully optimized on the electronic point of view, and prone to straightforward changes of control schedules.

Failure detection

When the M53 engine analog computer was being designed in 1976/1976, the emphasis was placed on the quality of electronic failure detection to safeguard the aircraft safety by reconfiguring to a hydromechanical mode. This accounts for the architecture then selected involving a reference channel. It was an initial form of redundancy, and we have fully explored this structure with the M53 computer.

The typical diagram of this structure is shown by figure 4.

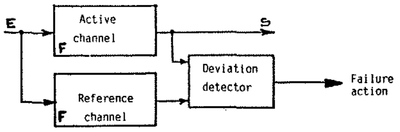

Figure 4 : Failure detection through a deviation detector

This type of monitoring is fully efficient to detect the anomalies of the function F even if the nature of the failures is not known, and, therefore, is well adapted to a complex function. Only those failures introduced by the deviation detector may lead to leaving a failure undetected, thus impairing the safety. Therefore the deviation detector must have a high reliability and its performance must be checked at regular intervals through an appropriate test.

This is not difficult, as this component is quite simple. On the other hand, the reference channel is as complex as the active channel, and its failures leads to false detections downgrading the success of the mission.

Another type of monitoring is shown by figure 5.

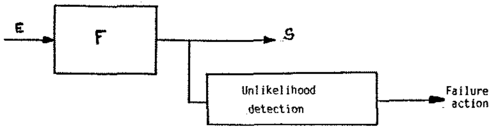

Figure 5 : Failure detection through detection of unlikelihood

This consists in checking if the output S remains within a reasonable range. If not, an anomaly is detected and the failure action is launched.

The advantage of this monitoring mode is its simplicity, although failures producing a wrohg value of S while remaining within the reasonable range cannot be detected.

A third type of monitoring mode consists of an integrity check. With a sensing potentiometer, for instance, this consists in detecting an open track in by measuring the current across the track. A zero current indicates an open track.

This type of monitoring is efficient, but assumes that the nature of the failures is known, which limits its application to simple systems.

As shown by the table of figure 6, these various monitoring modes have been introduced in the M53 computer, either individually or in combination.

FUNCTION	MONITORING
Fuel metering valve control	Deviation detector Integrity check
Exhaust nozzle control	Deviation detector
Rotation speed sensors	Unlikeness Deviation detector
Power lever sensors	Unlikeness Integrity check Deviation detector
T7 thermocouples	Unlikeness Deviation detector
Pressure sensors	Unlikeness Integrity check
Nozzle area sensors	Deviation detector
AB fuel metering valve controls	Deviation detector Integrity check
Fan flow regulator control	Deviation detector Integrity check

Figure 6 : Typical monitoring modes

Other failure detection devices adapted to the digital techniques were introduced in the digital computer design.

For instance, a "Watchdog" monitoring mode is used to check that a programme has been satisfactorily carried out. The principle is as follows :

- at a predetermined point in the programme, the programme controls the start of a time count,
- at a second point later in the programme , the time count is stopped.

If this second action does not occur before a given time, the watchdog will indicate that an anomaly has occured (for instance, inadvertent looping) and the failure actions are launched.

Computer self-test

As stated earlier, the system must be tested periodically. We have selected to do this test each time the supply power is applied. This is the computer self-test. Its purpose is to check for failure which would prevent the computer from detecting its own failures (dormant failures of monitoring circuits). This is achevied by stimulating one channel deliberately and ensuring that this channel will launch the failure actions. This test is run under the control of a specific programme which start each time the power is applied to the computer provided the power lever is in the "shutoff" position. All monitoring circuits are stimulated in succession. In case of anomaly, a failure signal is displayed. Otherwise, as soon as the self-test is completed (5 seconds) the computer is acknowledged as being in operation order.

Software safety

With the software, the concept of failure probability does not apply since a programme is a sequence of fully determined instructions to convert input data into output data. Any defect in the programme will remain there permanently as residual design faults which will be hidden as long as a particular combination of inputs will not activate these faults. E being the set of valid input combinations, it can be said that there is a sub-set EAF of inputs activating the faults.

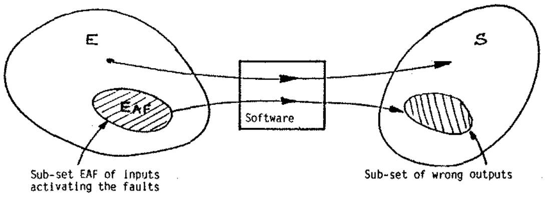

Figure 7 : Software inputs - outputs graph

Therefore, the failure probability is the probability to have an input configuration highlighting a defect (sub-set AEF). In this manner, a failure occurence can be considered as an random failure and it becomes possible to talk of software reliability. Therefore this reliability is directly related to the number of residual faults and, consequently, to the design quality. Obviously, software size and complexity have a direct effect on software reliability, and such reliability is improved by the elimination of residual design faults.

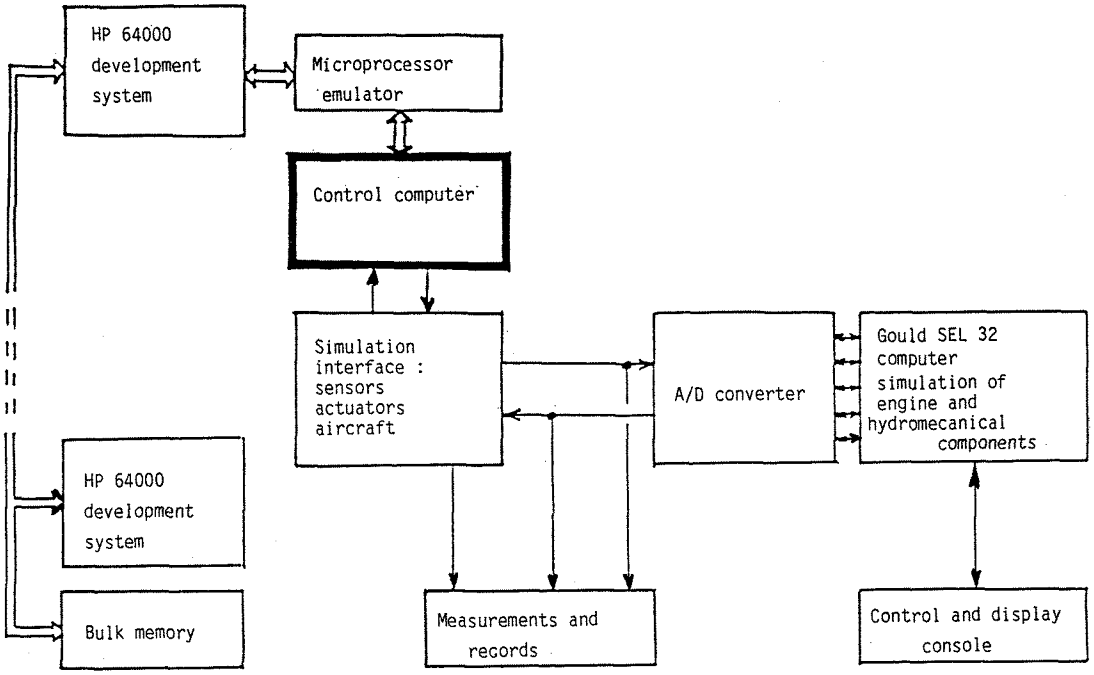
HP 64000 development system
Microprocessor emulator
Control computer
Simulation interface : sensors actuators aircraft
A/D converter
Gould SEL 32 computer simulation of engine and hydromecanical components
HP 64000 development system
Bulk memory
Measurements and records
Control and display console

Figure 8 : Software production and validation system

Avoiding design faults is based on the use of a software development methodology devised from the well known documents RTCA DO-178 and GAM 17.

Its principle consists in breaking down the software into modules in a sufficient number to simplify the design of each module and facilitate its test. The module interfaces are clearly identified after coding and individual testing, these modules are progressively grouped together during an integration phase.

Each development phase is followed by a test phase to guarantee the quality of the final product.

We have strictly applied this methodology to the M53 digital computer software design. We thus became familiar with this design procedure and the resulting product performed very well.

To support this design work, software production and validation facilities have been implemented. These facilities are briefly described in figure 8, and are used for the following purposes :

- Software design
- Software/hardware integration
- Validation of the software operating in an actual control computer physically installed and rig tested
- Preparation of required documentation
- Configuration control

Reconfigurations

When a failure is detected and identified, the control system can be reconfigured to maintain a satisfactory operation while accepting, in some cases, some performance loss. Two categories of reconfigurations aiming at improving the safety level were developped and introduced in the M53 engine control system :

- electronic reconfigurations
- hydromechanical reconfigurations.

The first category includes digital reconfigurations of aircraft parameters or engine sensors to a fixed, predetermined value in order to achieve operating safety. The second category includes the hydromechanical backup and the emergency fuel control.

Figure 9 summarizes the various modes of hydromechanical reconfigurations depending on the failure location and the engine operating case when the failure occured.

The hydromechanical backup mode is a fully hydromechanical mode of operation of the main engine control made possible by force balances built in this control. This mode of operation can be controlled from the pilot's power lever.

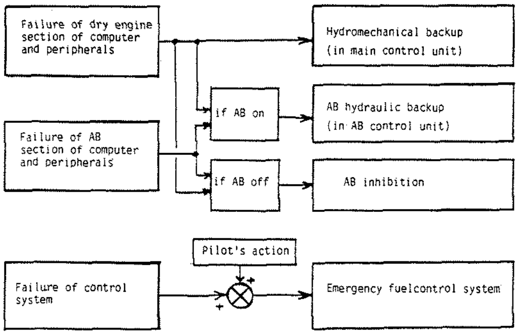
Failure of dry engine section of computer and peripherals
Hydromechanical backup (in main control unit)
if AB on
AB hydraulic backup (in AB control unit)
Failure of AB section of computer and peripherals
if AB off
AB inhibition
Pilot's action
Failure of control system
+
+
Emergency fuelcontrol system

Figure 9 : Hydromecanical reconfigurations

The afterburner hydraulic backup is also entirely hydromechanical. This control maintains a constant AB fuel/air ratio avoiding a total loss of the afterburner during a flight phase where its use is necessary (e.g. heavy take off weight). Therefore, this mode of operation is not controlled by the pilot.

The emergency fuel control system uses a fully separate fuel pump and control unit. It provides a controllable thrust to fly the aircraft back to its base in case of serious main control system failure. This backup system is selected on a deliberate action of the pilot and within a limited flight envelope.

The design and development of these reconfigurations were followed by operational checks in the complete aircraft flight envelope in order to ensure that switching did not cause unacceptable malfunctions.

Assistance to maintenance

To facilitate the analysis of failures and identification of accessories to be replaced, the M53 engine computer also incorporates the following features :

- Memorizing of detected failures
- Shaping of signals sent to be crash recorder
- Shaping of signals sent to the life cycle counter which monitors 10 engine components.

Conclusion

With these few briefly presented examples, you have been able to understand that most of the concepts used in an advanced digital control system have been explored by SNECMA during the design and development of the M53 engine control system.

In this manner, the development of new digital full authority and redundant control system (RENPAR) is based on a considerable experience acquired from a major program, which will allow SNECMA to tackle the development of new engine control system.