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REDUNDANT CONTROL UNIT FOR AN ADVANCED MULTISPOOL ENGINE

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Abstract

Since the control of modern multispool engines is very complex, more and more engine controllers are today based on digital technology and no longer on hydromechanics. In the following a full authority redundant digital engine control unit (DECU), jointly developed by Bodenseewerk and Motoren- und Turbinen Union (MTU), will be used as an example to show the realization of such a controller.

The advantages and disadvantages of digital technology will be elaborated and compared to each other. The concept of the controller structure will be described with particular respect to the software design. Finally software verification methods and methods for validating the complete controller will be presented.

1. Introduction

The basic functions of a jet engine controller have only insignificantly changed since the first engines have been built. As for historical reasons the development of these controllers was based on hydromechanic technology a considerable number of the presently used engine controllers are realized in this technology. With the jet engines becoming more and more complex and the control function requirements changing it has only in the last years become necessary to use new technologies in this field.

At first analog-electronic engine controllers were built which were however very soon replaced by digital engine control units resulting from the microprocessor development.

In view of their reliability these digital control units (DECU) are to be built redundant unlike the hydromechanical predecessors. The fast microprocessors allow short sampling periods adequate for modern engines which accelerate in the uncontrolled mode in less than 2 seconds from idling speed to maximum.

Besides the possibility to implement advanced control laws one of the main benefits using microprocessors is the improvement of the maintainability of the system.

2. Tasks of an Engine Control Unit

The basic functions which an engine controller has to fulfill were already defined for the hydromechanical controllers.

a) The specific fuel consumption shall be optimal.

b) Thermal and mechanical overstress shall be avoided.

c) The controlled parameter which is preselected by the throttle control lever (rotation speed, pressure ratio) shall be independent of air speed and flight altitude.

d) The acceleration shall be fast with no compressor stall.

e) During deceleration or idling speed the combustion shall not be interrupted.

f) The engine handling shall be optimal (for example linear relation between the angle of the power lever and the rotation speed or thrust).

In the realization of these tasks a difference is made between single and multiple output control. The single output control varies only the fuel flow, whereas in the multiple output control the fuel flow and - in addition - the compressor guide vanes and the nozzle are varied.

3. Advantages of the Digital Technology

Using some examples it shall be tried to demonstrate the possibilities and advantages of digital technology which are of particular importance for the engine control (1,2,3).

o Integrated Engine and Flight Control

By the integration of engine and flight control, which is possible by coupling the engine control unit to a flight data bus, the performance of the aircraft will be better and the engine will be protected from unneccessary overstress.

o Realization of complex Functions

In hydromechanical or analog-electronical controllers complex functions are realized in hardware and can only be modified with considerable effort. In digital systems this is easy because of programmable function generators.

o Reliability

The intelligence of digital controllers allows the application of methods of self-monitoring and analytical redundancy. By these methods the reliability of the system is increased.

o Testability

Basically improved test facilities such as an optional number of test points increase the system maintainability and reduce the operating costs.
Inspite of all these advantages the disadvantages of a digital system shall not be neglected. Due to its discrete nature and due to the delay caused by the calculation time of the microprocessor a digital control system has a lower stability than a comparable analog system. Future control systems containing the latest microprocessors will however increase the sampling frequency and reduce the delay so that these disadvantages can be neglected.

4. Design and Realization of the Digital Engine Control (DECU)

4.1 Computer Requirements

From the digital realization additional requirements result as compared to the hydromechanical control unit (chapter 2);

1) Improvement of the existing control laws.

2) The control laws shall be expandable so that it will be possible to minimize the fuel consumption, increase the engine life time and integrate flight control and engine control (2).

3) Unlike the hydromechanical controllers which have only an emergency system the controller shall be realized in a redundant design. By self-monitoring procedures the active controller lane shall automatically perform a switchover to the redundant lane in case of a failure.

4) Due to the in-flight recording of failure causes maintenance and repair of the controller can be done faster.

5) In a pre-flight test the condition of the controller shall be checked by a built-in test equipment (BITE).

6) The software shall be transparent.

4.2 Controller Structure

The DECU is a full authority digital engine controller for a modern multi-spool engine. Considering several conditions such as altitude and Machnumber the high-pressure and low-pressure speed, accelerations and the turbine blade temperature are monitored and controlled as a function of the throttle control lever (Fig. 4.1).

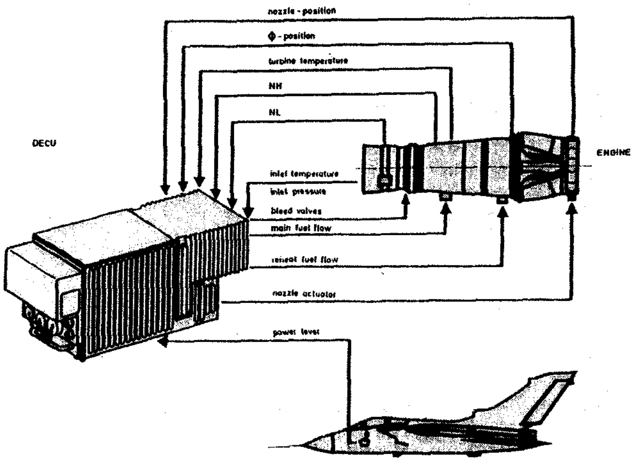

FIGURE 4.1 Tasks of the DECU.

Apart from the actuation of the bleed valves the actuator systems of the afterburner are controlled. The structure of the controller is presented in the diagram of figure 4.2.

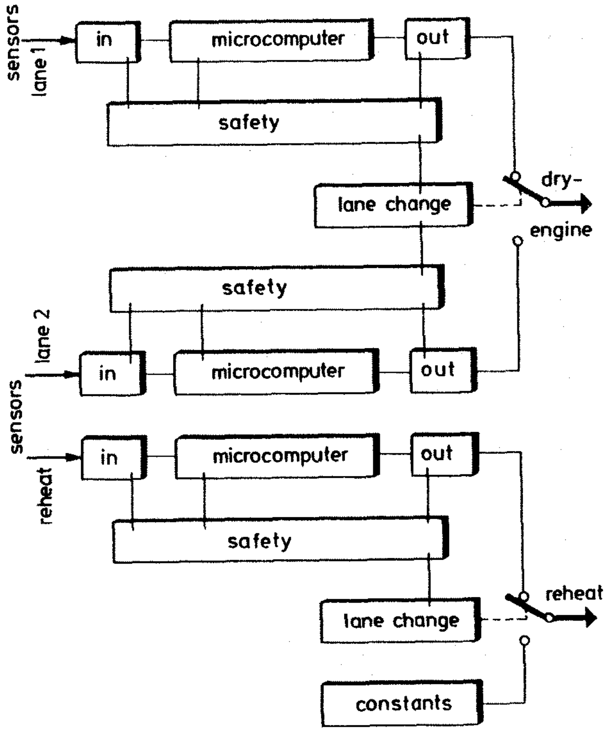

FIGURE 4.2 Structure of the DECU

The main component of each of the 3 lanes is a microprocessor. Both lanes of the dry engine controller are provided with their own analog data which are processed and digitalized in an interface. The actuator commands which are determined by the control program are digital-analog-converted and transmitted to the actuators. The blow-off valves are among others discrete-activated.

The safety system comprises a number of self-monitoring procedures (watchdog timer, estimating procedure,...) which are used for monitoring the control lanes. In case of a failure there is an automatic switch-over to the second lane. In order to ensure a smooth lane change the output signal of the passive lane is adapted to the value of the active lane by a data exchange (Fig. 4.3).

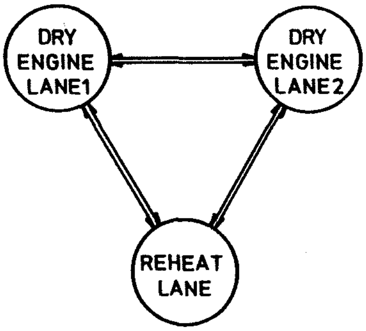

FIGURE 4.3 Data exchange

This data exchange is furthermore used for replacing a failed sensor in a second failure situation which might have been caused for example by a sensor failure in lane 1 and after the lane change has taken place by another sensor failure in the then active lane 2.

For the control of the afterburner there is only one lane. In case of a failure there is a switch-over to constant demands or the afterburner will be shut down. For improving the controller maintainability a failure identification module (FIM) is provided in which for instance all those parameters are recorded which are decisive for the lane change. Thus the rate of unconfirmed removals can be reduced and trouble-shooting can be facilitated.

Furthermore the BITE should be mentioned which allows to test the controller hardware. The controller-internal microcomputer is used for both the BITE and the FIM. It tests the following function modules of the controller:

1) safety system
2) micro-computer
3) analog-digital converters
4) interface circuits: analog inputs and outputs
5) interface circuits: digital inputs and outputs

The programm by which the dry engine is controlled in accordance with the above requirements has the structure as it is presented in Fig. 4.4.

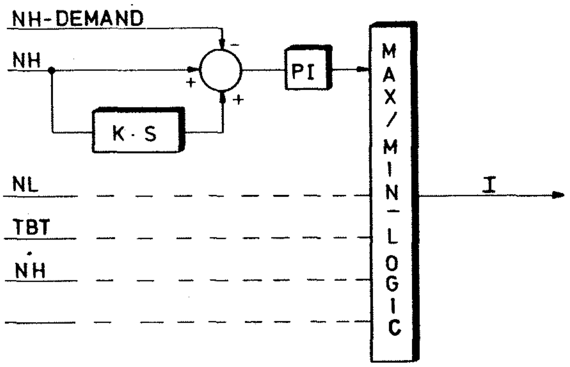

FIGURE 4.4 Block diagram of the control-logic

Depending on the amplitude of the individual signals one of the control loops will be active. The quality of the control behaviour and the interaction of the individual control loops depend on the gain factors of the individual control loops. Therefore it is extremely important to have procedures which allow a fast and cost-effective determination of the gain values for the control loops. The results of the optimization will then be verified by simulations.

4.3 Optimization of the gain factors

For the optimization of the gain factors of a controller there are basically two methods:

a) Using a linear model of the controlled system the gain factors are analytically determined with no consideration of sampling period and computer delay.
b) Using a non-linear model of the controlled system and considering the sampling period and the computer delay a computer-aided optimization of the gain factors is performed.

For the DECU the following way was chosen:

1) Derivation of a linear model of the controlled system consisting of engine and fuel metering system, the model being only valid for small disturbances from the steady state condition. Figure 4.5 shows the comparison between the linear and the non-linear model.

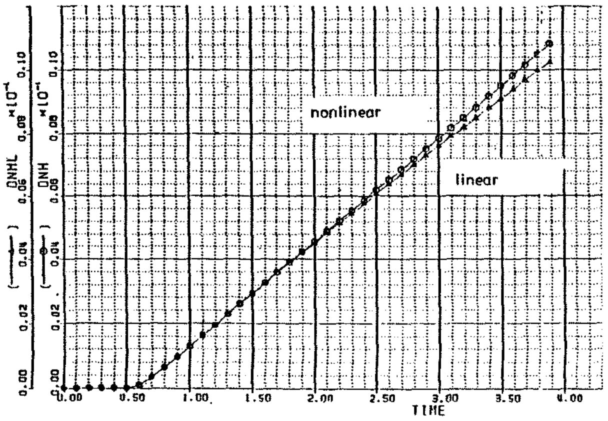

FIGURE 4.5 Comparison between a linear and a non-linear model of the controlled system (engine and fuel metering system)

2) Analytical determination of the gain factors applying methods of the classical control theory (continuous, no computer delay time) and using the linear model.

3) Computer-aided second optimization in the time domain on the basis of the gain factors, determined with the classical method. In this case the system is sampled and the computer delay time and existing non-linearities are taken into account. Figure 4.6 shows the procedure:

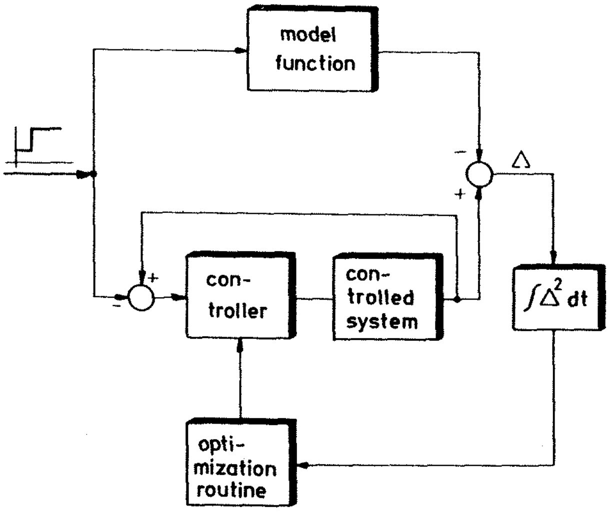

FIGURE 4.6 Block diagram of the computer-aided optimization of the gain factors

A given model function is compared to the transient response of the controlled system. By varying the gain factors the sum of the square derivations of both functions shall be minimized. Thus the gain factors are defined by the use of which the given model function can be best approximated.

4.4 Software

In digital systems particular attention is to be paid to the software development. The RTCA-DOC 178 (4) specifies general rules for the software development. One of the main items is the fact that the development is done step by step and that each step is individually tested. Only then the next step is released.

The different steps of the software development from the specification up to the validation are shown in Fig. 4.7.

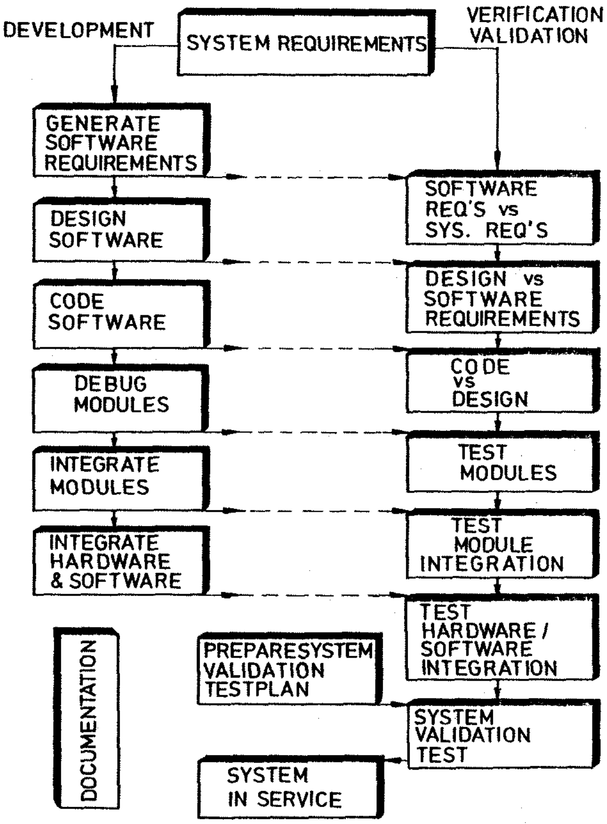

FIGURE 4.7 Block diagram of the software development

The accompanying documentation which is necessary for approving the system and which is required by the user is established separately for each step. The software design which is the main item of the development is designed hierarchically and top down.

The basis of the software development of the DECU are system block diagrams which represent the software-specific specifications. The block diagram for the control laws (Fig. 4.4) shows such a system block diagram.

After the software design the coding is done in a structurized higher organized language (HOL) using a host computer. This program presents the basis for programming the micro-computer.

In this case the coding is done on the host computer in PASCAL. The PASCAL program is then the basis of the pseudo code (structurized assembler) for the target computer (Fig. 4.8).

```
BEGINMODUL 'RGO2'
NDIF1   :=NHMX - NHID
PROD2   :=NDIF1 * R1
NHSO1   :=PRODZ + NHID
NHSO2   :=MAX (NHSO1, NHID)
NHSO    :=MIN (NHSO2, NHMX)
DELNH   :=ABS (NHSO - NH)
NHDOT1  :=K5 * NHDOT
DNH     :=NHDOT1 - NHSO + NH
(* BERECHNUNG DER VARIABLEN AUF-
 SCHALTFAKTOREN FÜR NH *)
CIRED   :=AFGEN (F10, NHC)
C1      :=CIRED/PTO
IF ARITHMETISCHER ÜBERLAUF
THEN AKKU := MAX
ENDIF
DNH 1   :=DNH * C1
ISO1    :=DNH1 * P1
ENDMODUL 'RGO2'
```

FIGURE 4.8 Pseudo code

4.5 Electric setup of a lane

In order to describe the electric setup of the different lanes one lane of the dry engine controller is used as an example (Fig. 4.9).

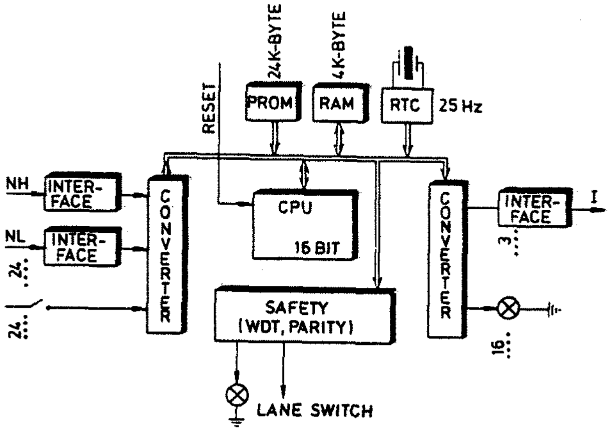

FIGURE 4.9 Electric setup of one lane

Up to 24 input signals are processed in an interface where for example the speed signals are frequency-voltage converted. An analog-digital converter digitalizes the signals and forwards them to the computer for further processing. The heart of the computer is a 16-bit microprocessor with a 24 K-Byte programmable read only memory (PROM) and a 4 K-Byte random access memory (RAM). The system sampling period is generated by an adjustable real-time clock.

The actuator signal for the fuel metering system which is calculated by the computer is converted in a digital/analog converter and processed in an interface for the actuator assembly.

Furthermore 16 discrete inputs and outputs each are available for both the scanning and the activation of switches, lamps, blow-off valves etc.

The computer hardware is monitored by special circuits (watchdog timer, parity check, etc.) which activate the lane change and the display for the pilot in case of a failure. The software failure detection procedures which are performed in the computer cause the same reaction as the hardware circuits.

4.6 Mechanical setup

The DECU is shown in Fig. 4.1o

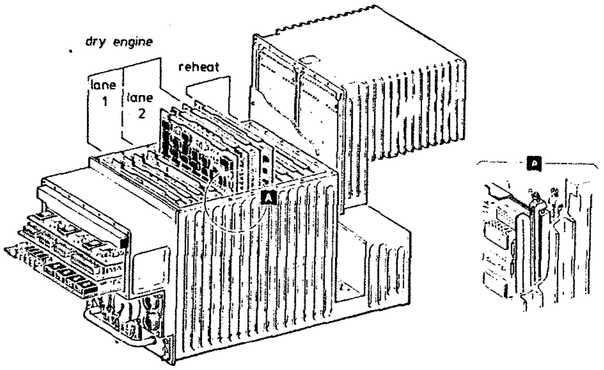

FIGURE 4.1o DECU

The form of the housing and the allocation of the unit and test connectors were designed in 3/4 ATR and in accordance with ARINC 4o4. The design aims particularly at reducing the temperature by choosing a suitable heat transfer from the electric components to the outer skin, at reducing the vibration stress and at obtaining a high resistivity against EM - fields.

Between the electronic components and the circuit board an aluminum sheet is located as a heat conductor. The circuit board assemblies are clamped into the housing. Thus a good heat transfer to the housing and a reduced vibration stress of the circuit boards are achieved.

The wirings between the circuit boards, to the unit connectors, to the PSU connectors and to the relays represent a separate assembly which is assembled outside the housing and then installed there.

The card connectors are mounted on a 2.5 mm motherboard on which part of the connections are realized as printed conductors.

5. System Test and Validation

5.1 Simulation

Parallel to the development of the hardware of the unit the controlled system and control program were implemented into the host computer. With these programs simulations were performed to verify the software. Some of these simulations are mentioned in the following:

- activation of the different control loops individually, in different combinations and as a whole
- acceleration and deceleration of the engine in the entire flight envelope
- influence of the opening and closing of the blow off valves
- influence of power extraction
- influence of signal noise
- improvement of the control by variable gain factors
- influence of the sampling period and the computer delay time.

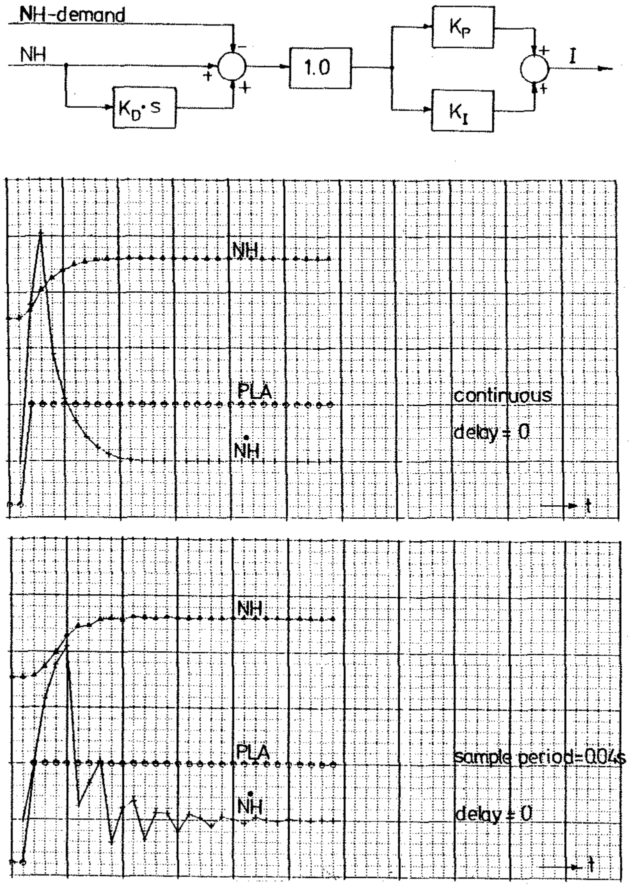

FIGURE 5.1 Comparison of transient responses (acceleration)

- continuous NH-loop (PID)
- sampled NH-loop (PID)

The influence of the sampling period and the computer delay time shall be discussed in greater detail:

Fig. 5.1 shows the transient response of NH and $\dot{N}$H of a proportional-integral-differential-(PID)-loop for an analog and discrete realisation with the same gain factors. The destabilizing effect of the sampling process is obvious (Fig. 5.1, below). After another optimization of the gain factors the sampled control loop is stable (Fig. 5.2 above)

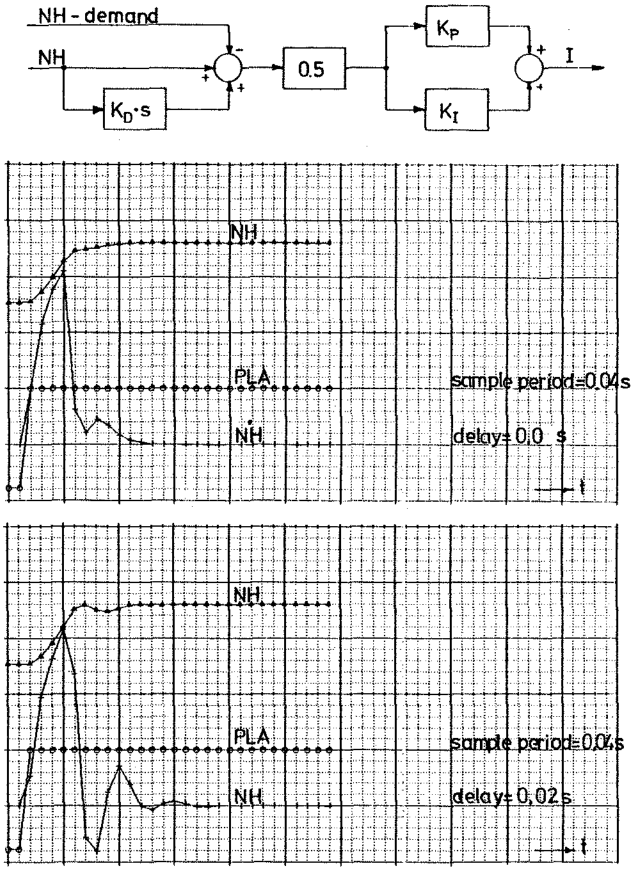

FIGURE 5.2 Comparison of transient responses (acceleration)

- sampled NH-loop without computer delay
- sampled NH-loop with computer delay

The insertion of the computer delay time destabilizes the control loop again (Fig. 5.2, below). This influence can be considered by the variation of the gain factors (Fig. 5.3,above), too.

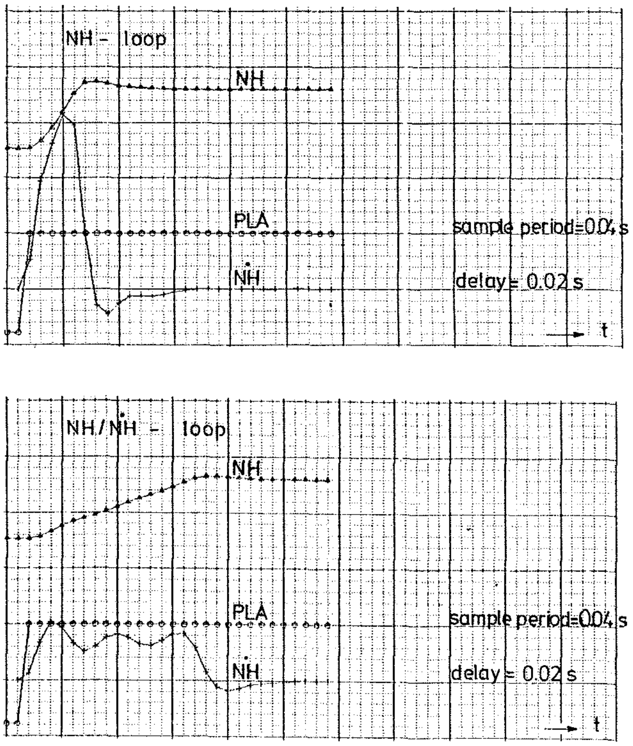

FIGURE 5.3 Comparison of transient responses (acceleration)

- o sampled NH-loop with computer delay
- o sampled NH/$\dot{N}H$-loop with computer delay

In all these simulations only the NH-loop was active and the Fig. 5.1, 5.2 and 5.3 (above) show clearly a high $\dot{N}H$-peak. By superimposing a $\dot{N}H$-loop this acceleration value can be limited to an arbitrary value (Fig. 5.3, below).

As a conclusion it can be said that sampling period and computer delay time have a destabilizing effect on the controlled system but that this effect can be compensated for by varying the gain factors.

5.2 Real-time simulation with hardware in the loop

When the software has been implemented into the controller hardware the controller is connected to an engine simulator and all functions are real-time tested. Acceleration and deceleration runs with different engine gains and the activations of the afterburner actuators and blow-off valves are tested.
These tests cover the entire flight envelope. Failure situations which cause the lane change are also simulated.

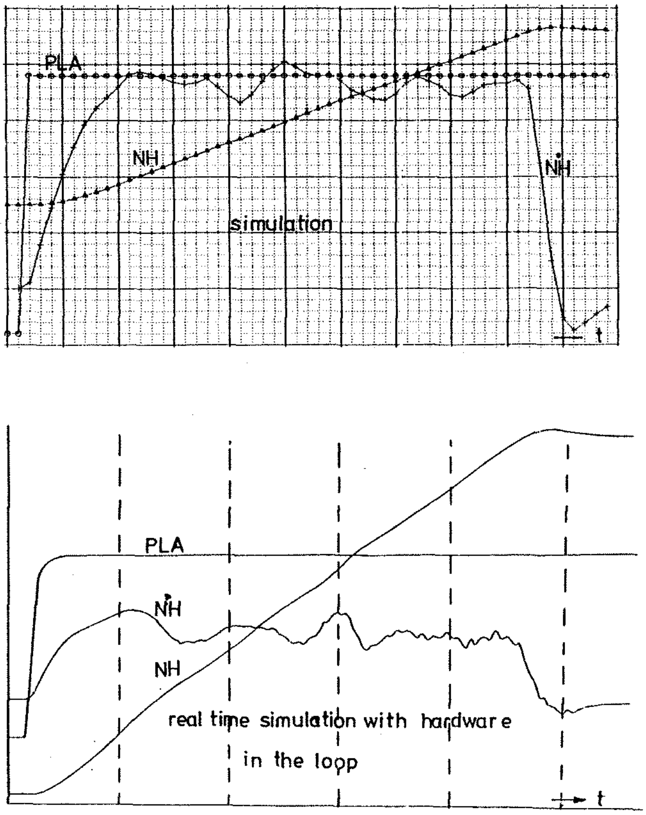

FIGURE 5.4 Comparison of transient responses (acceleration)

- o simulation
- o real-time simulation with hardware in the loop

Fig. 5.4 shows a comparison between the acceleration run of a simulation and the real-time simulation with hardware in the loop. A very good coincidence between both is visible.

5.3 Engine run

When the controller has succesfully passed the different tests it is checked for its real functionability in a test run on the engine. Fig. 5.5. presents an engine deceleration run. As a comparison the respective transient functions of a simulation are shown. A very good coincidence is obvious.

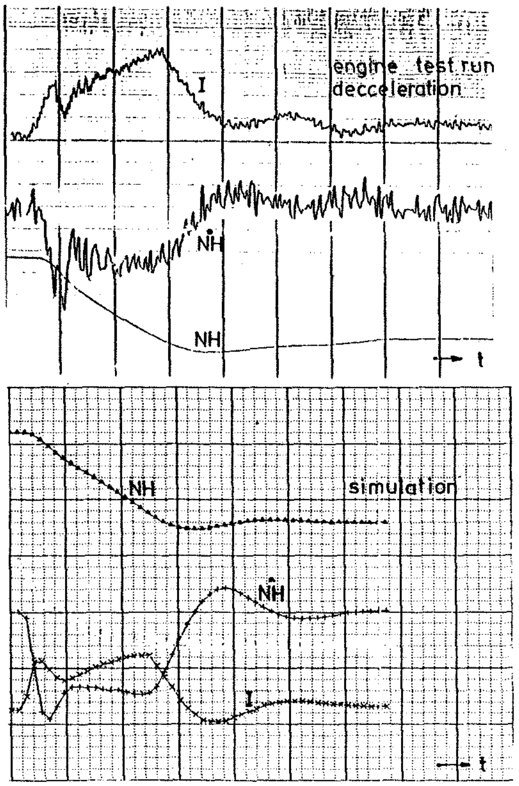

FIGURE 5.5 Comparison of transient responses (deceleration)

- o engine test run
- o simulation

6. Final Remarks

Using the DECU as an example the development of a digital engine control unit has been presented. The many advantages resulting from the introduction of digital electronics into engine control technology make up for the inevitable disadvantages, caused by sampling process and computer delay time. This is particularly due to the fact that the continuous improvement of the microprocessors allows to neglect sampling period and computer delay time. It is very essential to make full use not only of the increased reliability and improved maintainability of digital systems but also of the controller-internal intelligence. The advanced controllers will for instance be able to automatically perform an initial adaption to their engines.

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