UNIVERSITY POLITEHNICA OF BUCHAREST
Faculty of Aerospace Engineering
Department of Aerospace Sciences „ELIE CARAFOLI”

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DOCTORAL THESIS

ABSTRACT

Studii și cercetări experimentale privind adaptarea sistemelor de reglare automată a turbomotoarelor în scopul optimizării testării în bancul de probe.

Experimental studies and research on the adaptation of gas turbines control systems for test bench optimization.

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Content

INTRODUCTION

This doctoral thesis aims to carry out theoretical and experimental research on the realisation and adaptation of an automation control system for testing gas turbine engines, which includes the following elements: the start-up system, the fuel dosage system, the anti-surge valve control system, the command-and-control system, as well as the instrumentation and data acquisition system, which can also communicate on the ARINC 429 protocol. The system includes a novelty element, namely the STOP Emergency Stop line, consisting of another safety PLC, by means of which increased performance and safety in bench testing, increased data acquisition speed and response time minimization in case of emergency stop, can be obtained, thus protecting the gas turbine engine from possible unpredictable situations.

The structure of this thesis consists of: a short introduction where the main objectives are presented, followed by five chapters, and at closed by conclusions, a summary of the original contributions and the documentation used through the bibliography.

Chapter 1 aims to carry out a study on the currently existing automatic control systems for aviation gas turbine engines, revealing the evolution of the automatic regulation systems, both from the point of view of the gas turbine and from the point of view of the manufacturing technologies by comparing the block diagrams of some automatic regulation systems. The Chapter also presents the development of some of the most famous and used aviation gas turbines in history for different types of aircrafts, civil or military, represented by figures, where the component elements, aggregates and regulators from that time, can be identified, and reaching to the current state-of-the-art in automatic regulation systems for aviation gas turbine engines, typical for aircraft use, and also including the state-of-the-art of automatic regulation systems used for testing these types of engines on the test bench, as the latter are slightly different and with some particularities compared to the systems that come mounted directly on the aircraft installed gas turbine engine.

Chapter 2 presents, in the first part, the theory of automatic regulation systems, by exemplifying and explaining some terms through definitions, in order to make a connection and an easier understanding of how to display the block diagrams of automatic regulation systems and their logic of signals management and quantities, along with the transient processes that take place in aviation gas turbine engines, but also their regulation laws, highlighting through graphs the main operating curves and surge lines. The chapter also presents the level of performance achieved by current automatic regulation systems, their technical limitations, but also the contribution of modern electronics in automatic regulation systems and how this influenced their development and performance increase, as well as the design problems of automatic regulation systems, whose elements will receive special attention, and how certain elements shall be connected without influencing the proper functioning of the whole system.

Chapter 3 aims to present the classic architecture and equipment of the automatic control system in the test stand, the system being set in a basic configuration with just a PLC control unit, as well as a series of experiments that use the studied data acquisition and control system.

The block diagrams of the classic regulation system, equipped with the electric starter start-up system are presented. The auxiliary installations component elements and the communication between the acquisition system, auxiliary installations and the reference gas turbine engine are detailed, along with the presentation of the electrical diagrams and the equipment that compose this system, together with their basic characteristics, in order to provide understanding of the functionality and the connection between the measuring elements, the parameters, and the actuators, and, implicitly, the fuel dosage. The final part of the chapter presents the experiments carried out in the test cell with this command-and-control system and the Klimov TV2-117A reference engine, together with the personnel training procedures and the experimentation procedure.

Chapter 4 presents a comparative study of fuel control systems from different types of older and modern gas turbine engines, to show how and what types of parameters enter, as control factors, into the pump-regulator block and electronic units, and also the requirements of modern control systems and the software programs used for test systems on the bench. The chapter compares the various state-of-the-art systems equipping gas turbines both operating on test benches and viable to equip gas turbines, and presents the design requirements of automatic regulation and control systems, including the FADEC system, based on a selected group of gas turbines. These notions lay the foundation for creating a state-of-the-art bench testing system able to meet the necessary requirements.

Chapter 5 aims to carry out a comparative study on the automatic regulation systems focusing on their characteristics and weak points, in order to be able to establish the requirements for the new automatic regulation system and also the new architecture designed with the latest generation equipment, with high accuracies and speeds, in accordance with current requirements for testing turbofans and turboshaft engines, as well as an analysis of the electronic equipment from the point of view of state-of-the-art operating characteristics, corresponding to the new automatic regulation system. The analysis of the instrumentation block diagrams used for the gas turbine, but also for the auxiliary installations, shows the capability level of the automatic regulation system resulting from the configuration and the interconnection of all the blocks in the block diagrams presented previously.

In the last part of the chapter, the experiments in the test cell carried out with this automatic regulation system are presented, as well as the processing of the obtained data. The data resulting from the experiments using the new automatic control system that includes two PLCs and several information processing computers is compared to the data resulting from the experiments using the old system, the one comprised of only one electronic PLC control unit, where the emergency stop command line is integrated into the main software, mirroring the resulting graphs and determining the differences that occur.

At the end of the doctoral thesis, the author's conclusions, personal contributions, and future development directions will be presented together with the thesis bibliography and the personal bibliography used in the completion of this work.

CHAPTER 1

STUDY, EVOLUTION AND STATE OF THE ART OF THE AUTOMATION AND CONTROL SYSTEMS FOR AVIATION GAS TURBINE ENGINES

1.1.INTRODUCTION AND GENERAL NOTIONS ABOUT MTR AND SRA

It is known that aviation turbojet engines, used to equip modern civil or military aircrafts, represent complex technical systems, in which a series of transient and stationary physical and chemical phenomena occur in close interdependence, and as a result of which the energy contained in the fuel injected into the combustion chamber of the engine is ultimately converted into mechanical work for turboshaft engines, used in particular for helicopters, or in thrust, for turbojet engines, used in civil or military aircrafts [1-4]. The physical and chemical phenomena that occur in aviation gas turbines in the process of energy transformation are characterized by a whole series of quantities.

A certain quantitative ratio between the values of these quantities defines a certain operating regime. Therefore, the establishment of an aviation gas turbine operating regime implies the establishment of well-defined values for the quantities that characterize the physical and chemical phenomena that take place in the energy transformation process [1-4]. It is also obvious that the constant maintaining or modification, according to the needs, of the operating regime of the aviation gas turbine engine implies the constancy, or the corresponding modification, of the values of the quantities that characterize the physical and chemical phenomena that take place in the energy transformation process [3].

The operation of aviation gas turbines used to equip modern civil or military aircrafts is carried out in a wide range of operating regimes and flight regimes, that is over a wide range of altitudes and flight speeds [1-4].

The variation of the flight regime entails the modification of the external conditions in which the operation of the gas turbine engine takes place. These changes are perceived as disturbances and, as a result, they also entail the modification of the quantitative ratios between the quantities that characterize the physical and chemical phenomena that take place in the process of energy transformation and. therefore, entails the uncommanded modification of the operating mode of the gas turbine.

The uncommanded change of the regime imposed by the operation of the aviation gas turbine, in the process of exploitation, represents a negative phenomenon, for the exclusion of which immediate measures must be taken, by the pilot or by the automatic control system [1-4].

1.2.THE EVOLUTION OF MTR AND SRA REGARDING AGGREGATES AND REGULATION ELEMENTS

Between 1920 and 1940, the speed increased from approximately 150 to 350 km/h through evolutionary improvements in vehicle aerodynamics and engine technology, as previously discussed. At the end of the Second World War, the flight speed of propeller-driven aircrafts reached about 400-450 km/h, and the engine power of the largest reciprocating engines was about 5000 HP. This was almost the performance limit of the propeller propulsion system. Today, the propeller / piston engine is used only in smaller, low-speed aircraft used in general aviation.

In the late 1930s, further development began in jet propulsion, which promised much higher flight speeds than the ones achieved with propeller or piston engines. The experimental jet aircraft flew in the summer of 1939 (He-178), and in the early 1941, the first jet-on prototype began flight tests (He-280). In 1944, the planes were usually jet propelled and reached a speed of about 550 km/h (Me-262). In the early 1950s, jet aircrafts exceeded the speed of sound. In the mid-1950s, the first supersonic bomber (B-58 Hustler) emerged, and later the XB-70 reached Mach 3 speed.

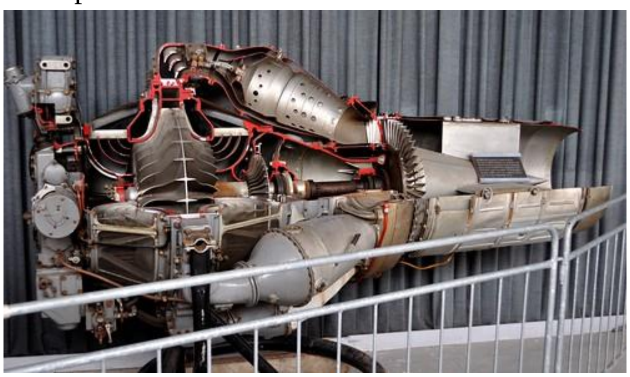
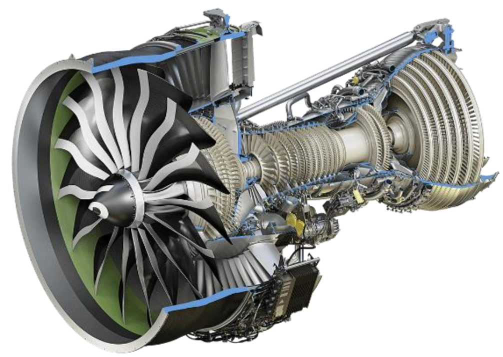



Figure 1.5. The RD45 turbojet engine, with a maximum thrust of 12 *TF* [8] The GE9X turbofan, with a maximum thrust of 50 *TF* [30]

Also in the 1950s, after more than 15 years of military development, gas turbine technology matured and very diverse applications began to develop, both for passenger and military aircrafts.

As it can be seen in this presentation, the systems and aggregates on the presented gas turbines are increasingly restricted and with fewer mechanical parts in the new models compared to the early models, their place being taken by electromechanical systems, in the middle of the series, and ending up by being completely replaced by electronic systems, FADEC type, the mechanical part remaining only the fine dosing element, but even here including coils and electronic control parts.

1.3.SRA CONFIGURATION FROM THE REGULATION LAWS POINT OF VIEW ON SOME KNOWN MTR TYPES

This chapter presents a comparative study of several control systems of different types, together with examples of the respective gas turbines. Through these examples, there are current D.E.E.C. or F.A.D.E.C. type systems.

The TV2-117A and TV3-117MT turboshaft gas turbines fuel control system.

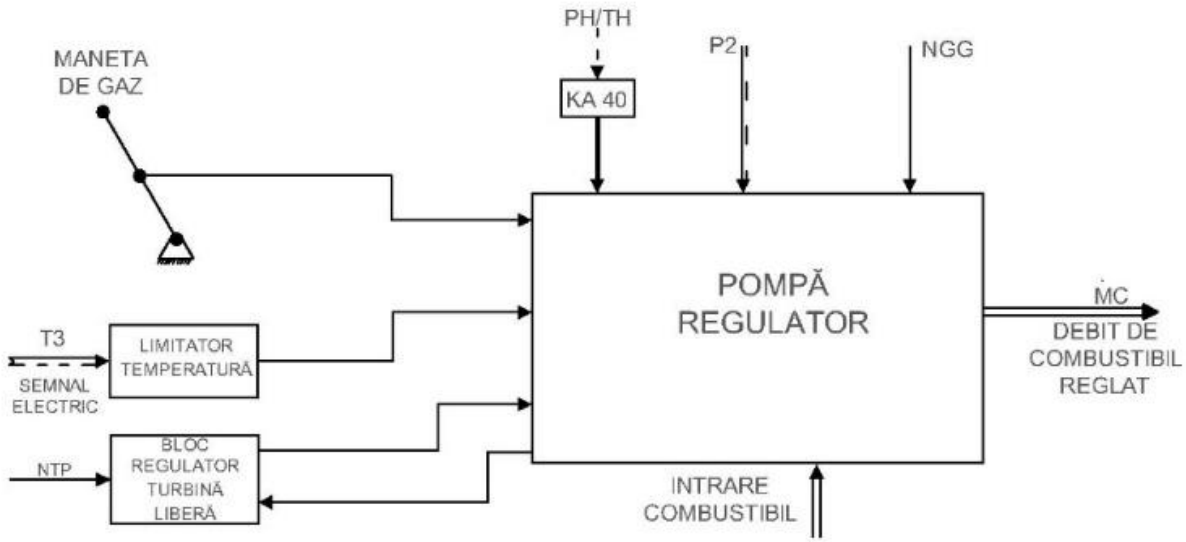


Figure 1.6. Hydro-mechanical fuel control system without electronic assistance [31]

The block diagram shows the fuel flow regulation system for the TV2-117A and TV3-117MT turboshafts, with a constant free turbine speed regulation law. The measured parameters are converted into hydraulic or mechanical signals and then enter directly into the regulator pump, which, together with the internal mechanical elements, performs fuel dosing according to the input signals.

The legend:

P_H/T_H – pressure and temperature at height H;
KA40 – signal converter pump;
M. G. – gas lever control;
M_c – regulated fuel flow;
T_3 – gas temperature at the inlet of the gas-generator turbine;
P_2 – pressure after the compressor;
N_GG – gas generator speed;
N_TP – power turbine speed;
Regulation law – constant N_TP speed;

The CFM 56-3 turbofan fuel control system

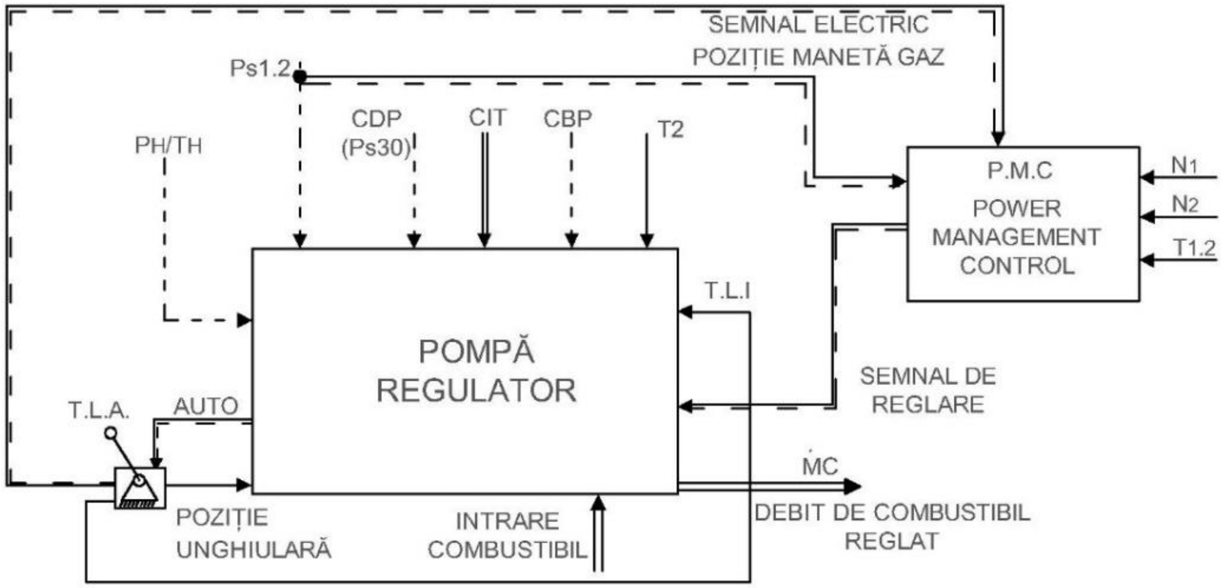


Figure 1.8. Hydromechanical fuel regulation system with electronic assistance [33]

The block diagram shows the fuel flow regulation system for the CFM-56-3 turbofan, with a fan speed regulation law, through the control of the low-pressure rotor speed N1. Some of the measured parameters enter directly into the regulator pump in the form of mechanical and hydraulic signals, while other measured parameters in the form of electrical signals, enter the electronic control unit P.M.C. which calculates and supplies the fuel flow regulation signal to the regulator pump according to P.L.A., PH/TH and Ps1.2.

The legend:

T.L.A. – "Throttle lever angle" (angle of the gas lever);
P_H/T_H – pressure and temperature at height H;
$P_{s1.2}$ – static pressure at the inlet of the F.S. fan;
T_2 – temperature at the inlet to the F.P. compressor;
$T_{1.2}$ – inlet temperature in F.S. fan;
P_2 – pressure at the inlet to the F.P. compressor;
CDP – compressor outlet pressure;
CIT – compressor inlet temperature;
CBP – compressor air sampling pressure;
T.L.I. – gas lever input signal;
N_1 – low rotor speed;
N_2 – high rotor speed;
M_C – regulated fuel flow.

The CFM 56-7 turbofan fuel control system

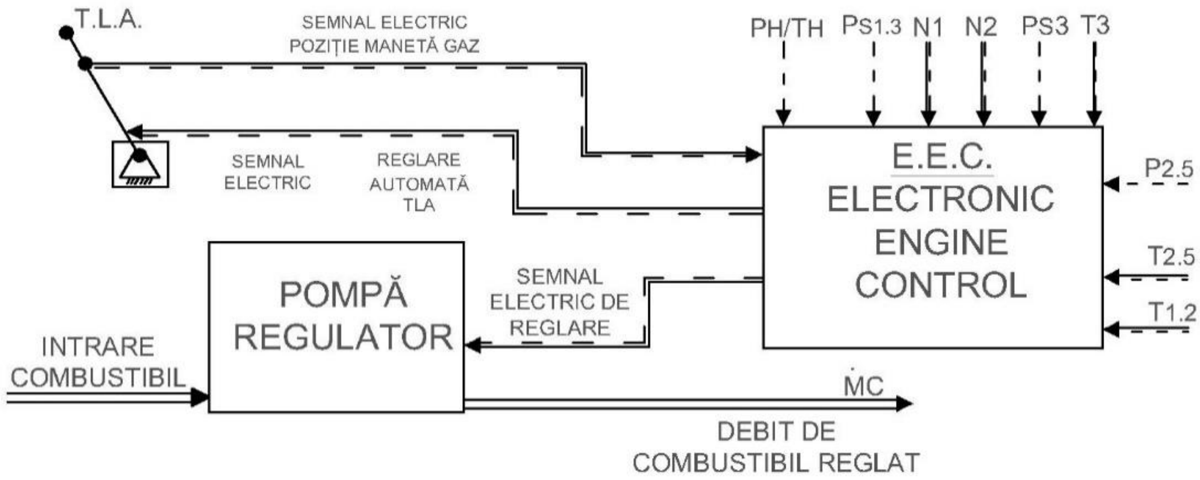


Figure 1.10. Electro-hydromechanical fuel regulation system with electronic assistance E.E.C. [35]

The block diagram shows the fuel flow regulation system for the CFM-56-7 turbofan, having with a fan speed regulation law, through the control of the low-pressure rotor speed N_1. Part of the measured parameters enter directly into the regulator pump in the form of mechanical and hydraulic signals, while other measured parameters, in the form of electrical signals, enter the electronic control unit E.E.C. which calculates and supplies the fuel flow regulation signal to the regulator pump according to T.L.A., P_H/T_H, Mach and P_s1.3.

The legend:

P_H/T_H - pressure and temperature at height H;
P_s3 – static pressure after the high-pressure compressor
N_1 – low rotor speed
N_2 – high rotor speed
P_s1.3 – static pressure at the outlet of the fan
P_2.5– pressure at the inlet of the high-pressure compressor
T_1.2 – total engine inlet temperature
T_3 – compressor outlet temperature
T_49.5 – high turbine discharge gas temperature (EGT)
T_2.5 – high compressor inlet temperature
T.L.A. – "Throttle lever angle".

The ST40M turboshaft gas turbine fuel control system

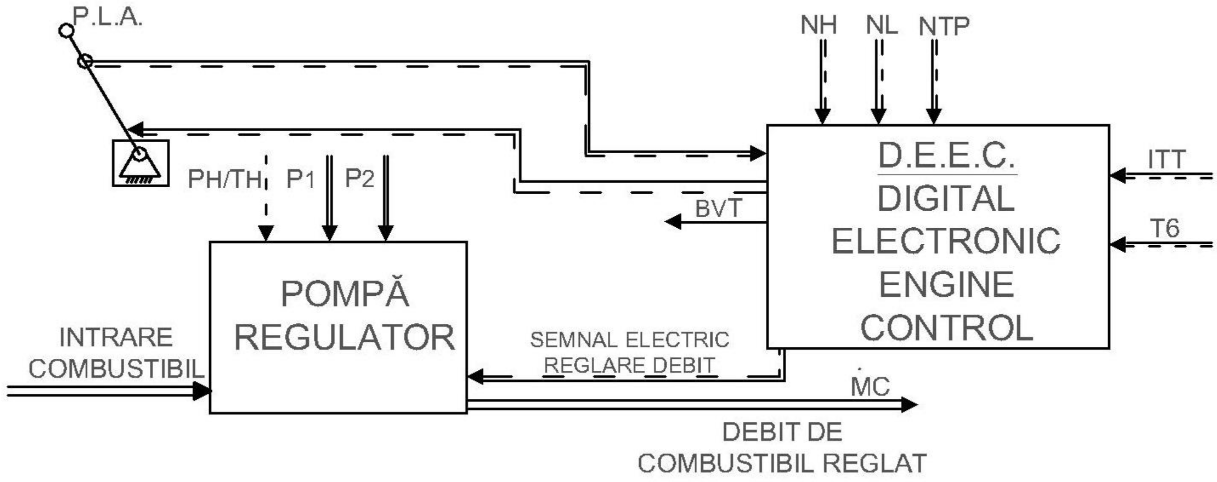


Figure 1.12. Electro-hydromechanical fuel regulation system with D.E.E.C. electronic assistance. [37]

The block diagram shows the fuel flow regulation system for ST40M turboshaft gas turbines, with a variable free turbine speed regulation law. A part of the measured parameters enters directly into the regulator pump in the form of hydraulic and pneumatic signals, and a part enters the D.E.E.C electronic unit in the form of electrical signals. The D.E.E.C unit calculates and supplies the electrical control signal to the regulator pump for optimal fuel dosing.

The legend:

P_H/T_H - pressure and temperature at height H;
N_H - high rotor speed
N_L – low rotor speed
N_{TP} – power turbine speed
I_{TT} – temperature between low turbine and power turbine
P_1 – fuel supply pressure
P_2 – fuel outlet pressure
T_6 – temperature at the outlet of the power turbine
P.L.A. – power lever position
BVT – anti-surge valve signal

The TFE-731 Turbofan fuel control system

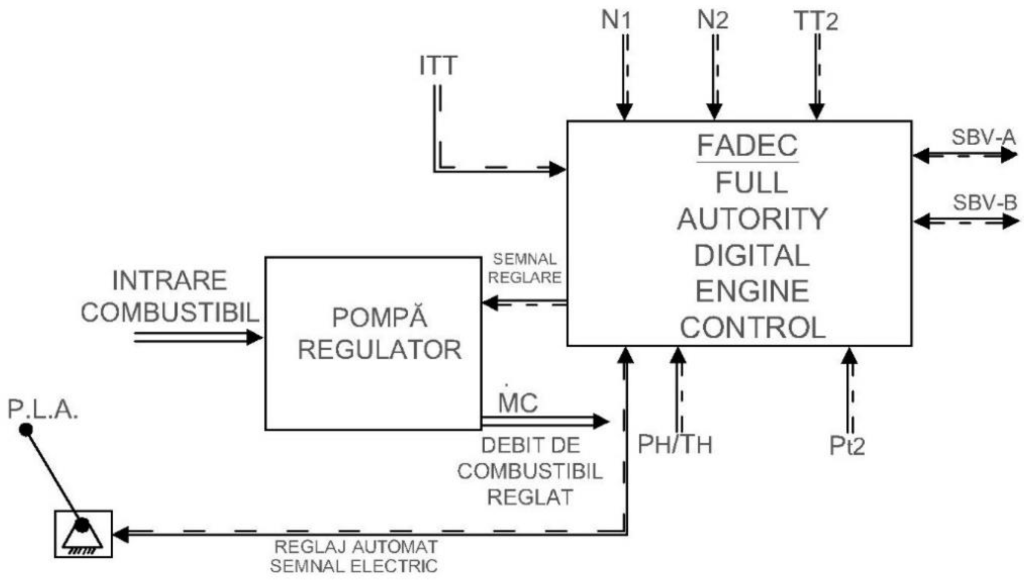


Figure 1.14. Electro-hydromechanical fuel regulation system with FADEC electronic assistance [39]

The block diagram shows the fuel flow regulation system for the TFE-731 turbofan, with a fan speed regulation law, through the control of the low-pressure rotor speed N_1. The measured parameters enter directly into the FADEC in the form of electrical signals. The FADEC electronic unit calculates and provides the fuel flow regulation signal to the regulator pump according to the P.L.A, PH/TH, no. Mach, T_T2 and P_t2.

The legend:

P.L.A. – throttle lever position
P_H/T_H - pressure and temperature at height H;
T_T2 – total temperature at engine inlet
P_t2 – the total pressure at the engine inlet
N_1 – low rotor speed
N_2 – high rotor speed
I_TT – turbine stage inlet temperature
SBV-A – anti-surge valve signal 1
SBV-B – anti-surge valve signal 2

The CFM-LEAP turbofan fuel control system

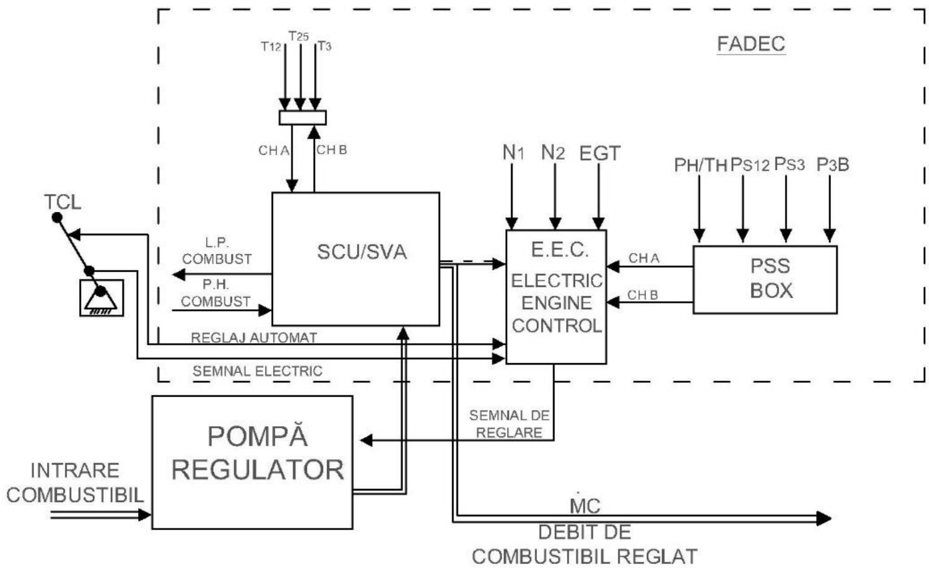


Figure 1.16. Electro-hydromechanical fuel regulation system with FADEC electronic assistance [41]

The block diagram shows the fuel flow regulation system at the CFM-LEAP turbofan with a fan speed regulation law, through the control of the low-pressure rotor speed N_1. The measured parameters enter directly into the FADEC in the form of electrical signals. The FADEC electronic unit is divided into several subsystems, which separately take the measured parameters from different sections of the engine and transmit them to the E.E.C electronic unit. which calculates and supplies the fuel flow regulation signal to the regulator pump according to T.C.L., PH/TH, Mach, T_2.5 and P_s12.

The legend:

P_H/T_H - pressure and temperature at height H;
P_s12 – inlet pressure in the fan
P_s3 – the pressure after the high compressor
P_3b – air sampling pressure
N_1 – low rotor speed
N_2 – high rotor speed
EGT – turbine gas temperature
T_12 – total engine inlet temperature
T_2.5 – high compressor inlet temperature
T_3 – high compressor outlet temperature
T.C.L. – "Thrust control lever"
E.E.C. – electronic engine control
PSS BOX – pressure subsystem
SCU-SVA – Split Control Unit / Servo Valve Assembly

From this comparison of the fuel control systems for different types and classes of gas turbines, designed and manufactured in different years, we can see the transition from hydromechanical systems for regulating the fuel flow, to electronic systems for measuring and dosing the fuel flow, as electronics, and particularly integrated circuits, such as processors and microprocessors that can be programmed with mathematical functions to provide at the output the flow regulation signal, calculated according to the measured electrical parameter have advanced.

1.4.STATE OF THE ART OF SRA FOR AVIATION GAS TURBINE ENGINES

The evolution of gas turbine engines has led to increased demands for engine control systems to increase rotational speed and improve fuel economy. These demands have generated a widespread use of electronic control systems. The previous generations of such systems, namely the ECUs (electronic control units), which used the concept of surveillance, were introduced in the 1970s and can be found on a large number of aircrafts operating today.

As these examples show, FADEC supports efforts to increase performance and reliability and reduce overall costs by enabling a system that contains the EEC (or ECU), where extensions may be added to monitor the characteristics of the aircraft engine.

FADEC systems are currently in operation on a large number of aircrafts, some examples being: the new F-18E / F35 and Eurofighter military aircraft and the Airbus A320, A321, A380, Boeing 737, Boeing 747 and Boeing 777 civil aircraft.

1.5.STATE OF THE ART OF SRA FOR MTR TESTING IN THE TEST BENCH

Current systems for aviation gas turbine testing are mainly composed of a Server and one or more computers operating in the in industrial mode; the server must be powerful enough to handle all the information from the other PC systems in the network. It is known that very high data acquisition speeds can be reached, so the server system must be able to meet the requirements.

In addition to the computational technique, the systems for testing aviation gas turbines, in the test stand must include one or more software programs, for managing the measurement and control equipment, but also for programming the test for each dedicated gas turbine.

Each control block can be programmed separately according to a logic programmed according to each individual motor and its operating criteria.

CHAPTER 2

TRANSIENT PROCESSES AND REGULATION LAWS OF AVIATION GAS TURBINE ENGINES

2.1.THEORY OF AUTOMATIC CONTROL SYSTEMS

Designing a control system for an engine logically begins with choosing the basic operating concepts (commonly known as control modes) for each required control element. It proceeds in a sequence roughly as follows:

a) Engine requirements and available signals or parameters are evaluated to select the control mode that will provide the best operation;
b) The types of control regulators and computers to be used are selected;
c) Special system problems such as fuel pumping, metering or injection (into burners) are assessed and appropriate components are designed;
d) The stability requirements and basic performance requirements of the system are evaluated;
e) The ability of the control components to meet the physical requirements related to mechanical strength, environment and vibrations resistance is established;
f) The final system is evaluated by analysis or testing to establish its ability to perform as required under the actual operating conditions.

Each step in this design sequence is closely related to the design and performance requirements of the engine on which the controls will be used [6,48].

2.2.DESIGN REQUIREMENTS OF REGULATION AND AUTOMATIC CONTROL SYSTEMS

The ability to adjust transient performance and steady state performance is a distinct advantage of feedback control systems. To analyse and design control systems, we need to define and measure the performance of a system. Then, based on the desired performance of a control system, system parameters can be adjusted to provide the desired response. Because control systems are inherently dynamic systems, performance is usually specified both in terms of the time response for a given input signal and in terms of the resulting steady-state error.

The design specifications for control systems normally include several indices of time response for a specified input command, as well as a desired steady-state accuracy. However, often in the course of any design phase, specifications are revised to reach a compromise. Therefore, specifications are rarely a rigid set of requirements, but rather a first attempt to list a desired performance.

The design problems encountered in discrete data control systems are essentially similar to those encountered in the design of continuous data control systems. Basically, a process has to be controlled so that its output behaves according to prescribed performance specifications.

For the design of the required physical component, the selection of the specific control modes that will satisfy the performance requirements of the motor is necessary before a basic control concept can be established. The following steps will be required:

1. Defining the control requirements;
2. Selecting the control mode;
3. Determining the type of fuel and the fuel supply system;
4. Selecting the type of power servo drive for controlling elements with variable geometry;
5. Selecting the methods for measuring the necessary parameters;
6. Choosing the types of control computers (FADEC);
7. Selecting the accuracy to be used for each controlled variable.

2.3.TRANSIENT PROCESS AND REGULATION LAWS OF AVIATION GAS TURBINE ENGINES

Cold drive regime

In order to achieve the cold drive regimes, it is necessary to supply power to the gas turbine rotor from an external source. For this, a special starting device is used, namely a starter. The power produced by this starting device mainly ensures the overcoming of friction and the acceleration of the rotor so that in the combustion chamber the necessary conditions for the ignition of the fuel-air mixture are reached [3,56].

In this phase, the power consumed by the compressor to compress the air is negligible compared to the power consumed to overcome friction.

On the compressor characteristic curve, the lines of the cold drive regimes adjoin the self-rotation regimes, which represent limit cases for the cold drive regimes.

The curves ‘equations for the cold drive regimes can be written as:

$$\frac{\dot{M}_a \cdot \sqrt{T_1^*}}{P_1^*} = A_3 \cdot sin\,\alpha_3 \frac{\sigma_{ca}^*}{\sqrt{\tau_c}} \cdot \sqrt{\frac{K}{R}\left(\frac{2}{K+1}\right)^{\frac{k+1}{k-1}}} \cdot \pi_c \qquad (2.13)$$

where

$$\tau_c = \frac{T_2^*}{T_1^*} \qquad (2.14)$$

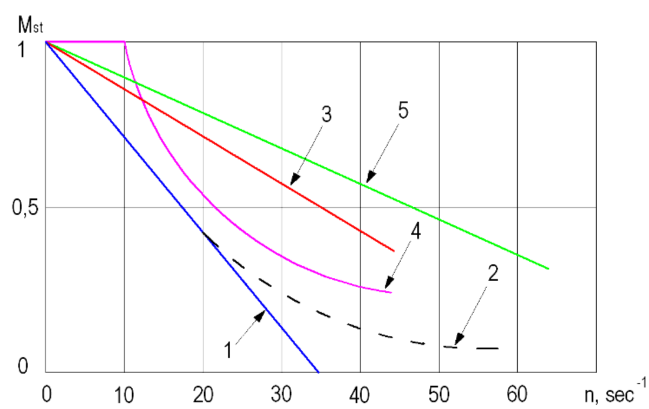


Figure 2.33. Mechanical characteristics of starting devices of different types [3,58] – right

1- Electric starter with parallel excitation;
2- Electric starter with series excitation;
3- Starter with turbocharger;
4- Hydraulic starter;
5- Pneumatic starter with low pressure air.

The power of the cold drive

The most common in aviation are electric and low-pressure pneumatic devices. Electric starters are used for low-power engines, and low-pressure air starters for medium- and high-power engines.

Each type of starting device is associated with a mechanic characteristic, usually presented in the form of the variation of motor torque on the output shaft of the starter, depending on its speed, this being a linear, hyperbolic, or parabolic function, or a combination of them. [3.53]

$$M_{st} = M_0 - b \cdot n \tag{2.15}$$

where:

M_0- initial motor torque on the motor shaft;

b - the constant coefficient for the given type of starter and for the transmission ratio from the starter shaft to the motor shaft;

n - motor shaft speed.

The actual variation of engine torque as a function of rpm is much more complicated, being largely a conventional representation.

Knowing the torque characteristic (Figure 2.34), the power characteristic can be determined:

$$P_{st} = M_{st} n = (M_0 - b \cdot n) \cdot n = M_0 \cdot n - b \cdot n^2 \tag{2.16}$$

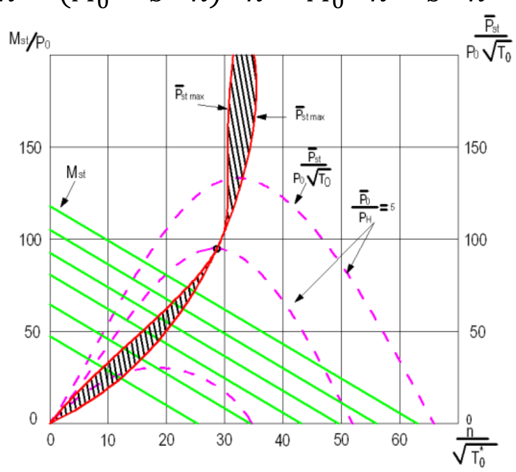


Figure 2.34. Mechanical characteristic of low-pressure air starter [3,58]

From the condition (dP_st)/dn = 0 we find the expression for the speed at which the power reaches its maximum value.

$$n \frac{M_0}{2 \cdot b_{Pmax}} \quad (2.17)$$

Substituting, we obtain the expressions for M_{Pmax} and $P_{st_{max}}$:

$$M0 \frac{M_0}{2 \cdot b} \frac{M_0}{2}_{Pmax} \quad (2.18)$$

$$P \frac{M_0}{2} \frac{M_0}{2 \cdot b} \frac{M_0^2}{4 \cdot b_{st_{max}}} \quad (2.19)$$

or:

$$n \frac{M_0}{b} Pmax_{st_{max}} \quad (2.20)$$

$$P \frac{M_0 \cdot n_{st_{max}}}{4}_{st_{max}} \quad (2.21)$$

Where: $n_{st_{max}}$is the maximum starter speed for which P_{st}= 0.

2.4.PERFORMANCE LEVEL AND LIMATIONS OF AUTOMATIC REGULATION SYSTEMS

Digitizing the automation system of a gas turbine requires the integration of automation software and the extension of the communication and security techniques. Potential benefits of digitization include reduced energy consumption and gas turbine downtime, improved quality, elimination of human error, improved planning and predictability. Cloud and wireless technology are crucial elements of the transition to digitalization.

CHAPTER 3

ARHITECTURE AND PERFORMANCE OF THE CLASSIC AUTOMATIC CONTROL SYSTEM WITH A SINGLE ELECTRONIC PLC

3.1 BLOCK DIAGRAM OF THE CLASSIC CONTROL SYSTEM WITH A PLC AND AUXILIARY INSTALLATIONS

In order to carry out experiments with the reference gas turbine, a number of auxiliary systems are required, which ensure the optimal operating conditions (fuel, air, oil, etc.), monitored and controlled by a PLC ("Programmable logic controller"). Also, the gas turbine is controlled by its own fuel metering system to which a throttle lever has been adapted, to adjust the position of the valve on the control pump, which also communicates directly with the PLC. The data displaying and processing, as well as the commands and control of the gas turbine, are carried out by means of a PC-type system, consisting of a desktop computer and a monitor for displaying the parameters in real time.

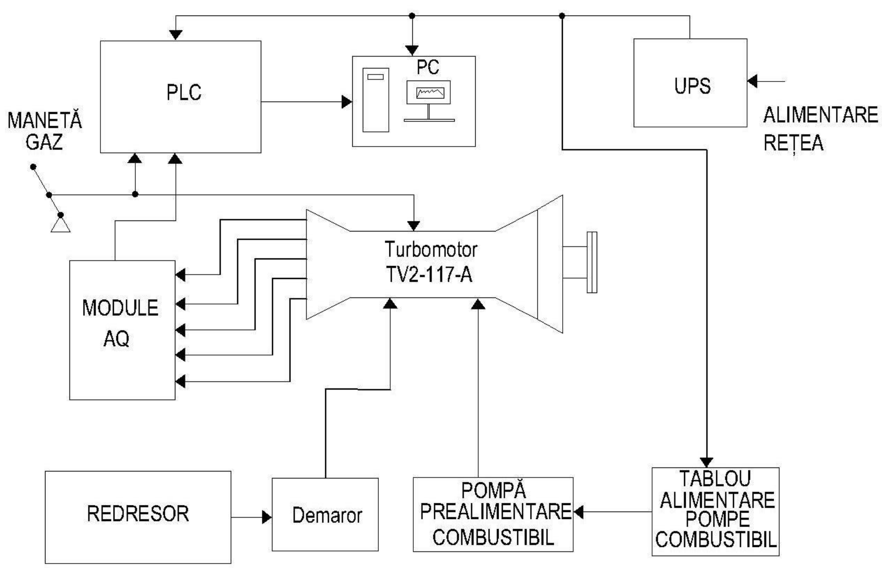


Figure 3.1. Block diagram of the classic gas turbine automatic regulation system together with the auxiliary installations

In the event of a power failure, the UPS system ensures for a short period of time the operation of the fuel system, the PLC and the PC system in order to be able to safely stop the gas turbine. The starter has an important role in the starting process and needs a high-power energy source through a rectifier that is also able to provide the starting ramp according to the reference gas turbine technical manual.

3.2 PRESENTATION OF THE TEST BENCH AUTOMATIC REGULATION SYSTEM EQUIPMENT

Programmable automaton GE 90-30

The automatic control, control and data acquisition system is based on the use of a PLC, Programmable Automatic, which is an industrial process computer that can be programmed according to the desired control loop and that easily communicates with the other equipment that makes up the automatic control system (pressure transducers, fuel dispenser, temperature sensors, temperature adapters, various control and actuation elements, linear actuators, level transducers and flow meters).

The Programmable Controller used for this application, in the automatic control system, is from the GE-FANUC 90-30 series [60]. It is programmed using the "LAD" type language, which is a graphical programming language based on the existence of predefined elements. Therefore, it is actually a graphical representation of Boolean equations, realizing a combination of contacts (input variables) and coils (output variables). The graphic symbols of the language are placed in the diagram, similar to the placement of contacts and relays in an electrical diagram.

The LAD language is made up of networks using graphical symbols. A program is executed from top to bottom, and a network is executed from left to right.

It has a number of functions that it can perform, depending on the requirements of the project and its programming:

- Displaying and processing parameters;
- Carrying out operating sequences: starting, idling, charging, connecting to the network, normal or emergency shutdown;
- Displaying the current time;
- Re-alarming the operator by colouring the displayed parameters when approaching the warning and protection parameters limits;
- Screens for different operating sequences;
- Technological diagrams in the screen component;
- Graphs with parameters;
- Displaying alarms;

- Automatic saving of important parameters during the start and stop sequences;
- Automatic saving of important parameters in the shutdown sequences, for a period of 5-10 minutes before triggering, with a frequency of at least one set of parameters per second;
- Saving "events" requested by the operator;
- Saving data and creating lists of parameters required for various reports, as required by the operator;
- Acquisition of current parameters, at desired time intervals;
- The possibility of calling saved files for start, stop and events in order to analyse the data;
- Explanatory legends related to the symbols used for the displayed parameters and for the components of the technological diagrams;
- Data transfer to PC for display and storage.

3.3 ELECTRICAL DIAGRAM OF THE INSTRUMENTATION AND DATA ACQUISITION SYSTEM

Figure 3.23 shows the electrical connection diagram of the main parameters acquired from the gas turbine with the GE 90-30 PLC acquisition system. Each parameter requires an individual connection with the PLC, and also a separate power supply.

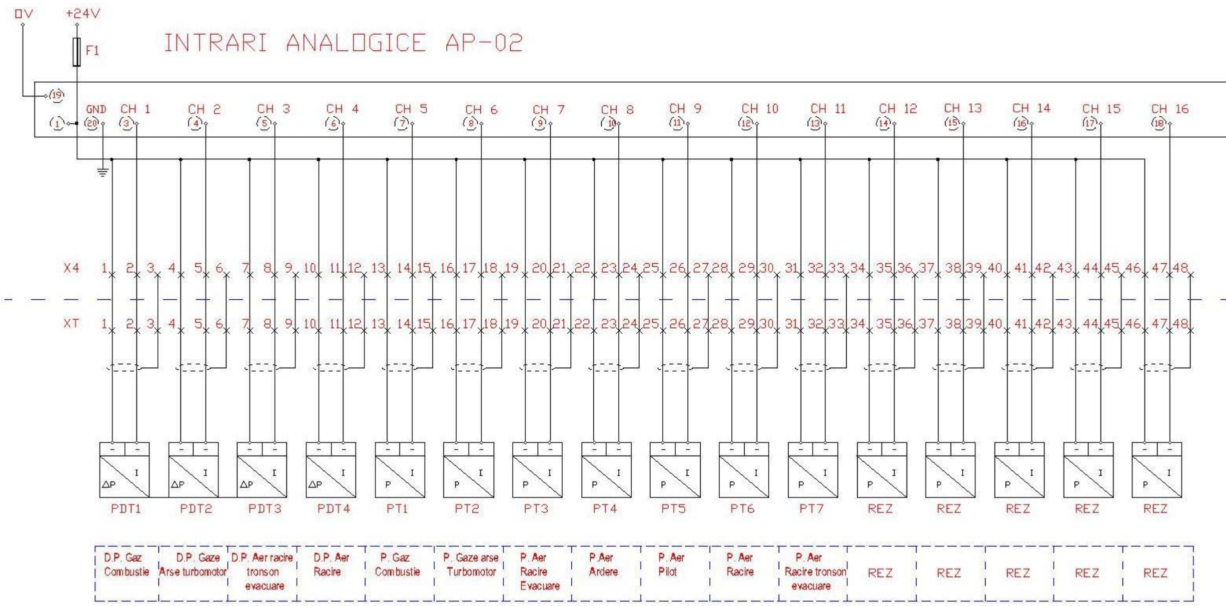


Figure 3.23. Diagram of gas turbine instrumentation for basic parameters

3.4 PRESENTATION OF THE CAPABILITY LEVEL OF THE TEST BENCH REGULATION SYSTEM

Considering the test bench capability, we define the maximum number of analogue or digital channels, input or output with the related specifications, the maximum acquisition speed, the stability of the test program operation, the complexity of the test software and the data saving and post-processing part.

- Digital voltage output control elements, with 32 channels on 12/24 VDC and a current of 0.5 A;
- Digital voltage input control elements, with 64 channels on 24 VDC and a current of 7 A;
- Analogue current input parameters in the configuration of 48 working channels, the working range being 4-20 mA;
- Analogue output type control elements for equipment that operate in voltage, 16 channels 0 ÷ 10 VDC;
- The imposed acquisition rate for all channels is 1 Hz, i.e., data save 1 / sec;
- Data is saved on the PC unit;

The software is programmed in Ladder Diagram graphical programming language, with a reduced possibility of highly complex logical development, being able to communicate with other equipment.

3.5 TEST BENCH EXPERIMENTS WITH THE CLASSICAL CONTROL SYSTEM

For test cell testing, the reference gas turbine was mounted, using mechanical support assemblies and ducting for the air intake and exhaust. Also, a basic instrumentation was made according to the technical manual of the engine [31], with a sufficient number of thermo-gasdynamic parameters, and links were created with the command-and-control elements.

It can be seen how after stabilizing the engine at a constant regime, fluctuations occurred in the engine parameters due to the imprecise control, but also to measurement errors. The most relevant factor in these types of tests is the achieved acquisition rate, which was of $r_a = 1$ s, insufficient for the precise control of a gas turbine. It is usually recommended that the acquisition rate is at $r_a=0.1$ s, or lower, to be able to make corrections on the control elements, but also to capture any real-time modification of the parameters.

3.6 ANALYSIS AND PRESENTATION OF DATA OBTAINED AT DIFFERENT TEST REGIMES

The experiment consisted of starting the reference gas turbine, bringing it to a stabilized idling regime and finally stopping it.

In the starting mode, the gas generator speed increases to an approximate limit of NGG=85% of the maximum allowed by the engine, and the starting curve is based on the electric starter that is commanded by two electric rectifiers to ensure all the necessary consumption conditions. Therefore, after reaching the maximum allowed start-up limit, the gas turbine drops to the regime of NGG=65% which represents the idle regime, and stabilizes in that range of values.

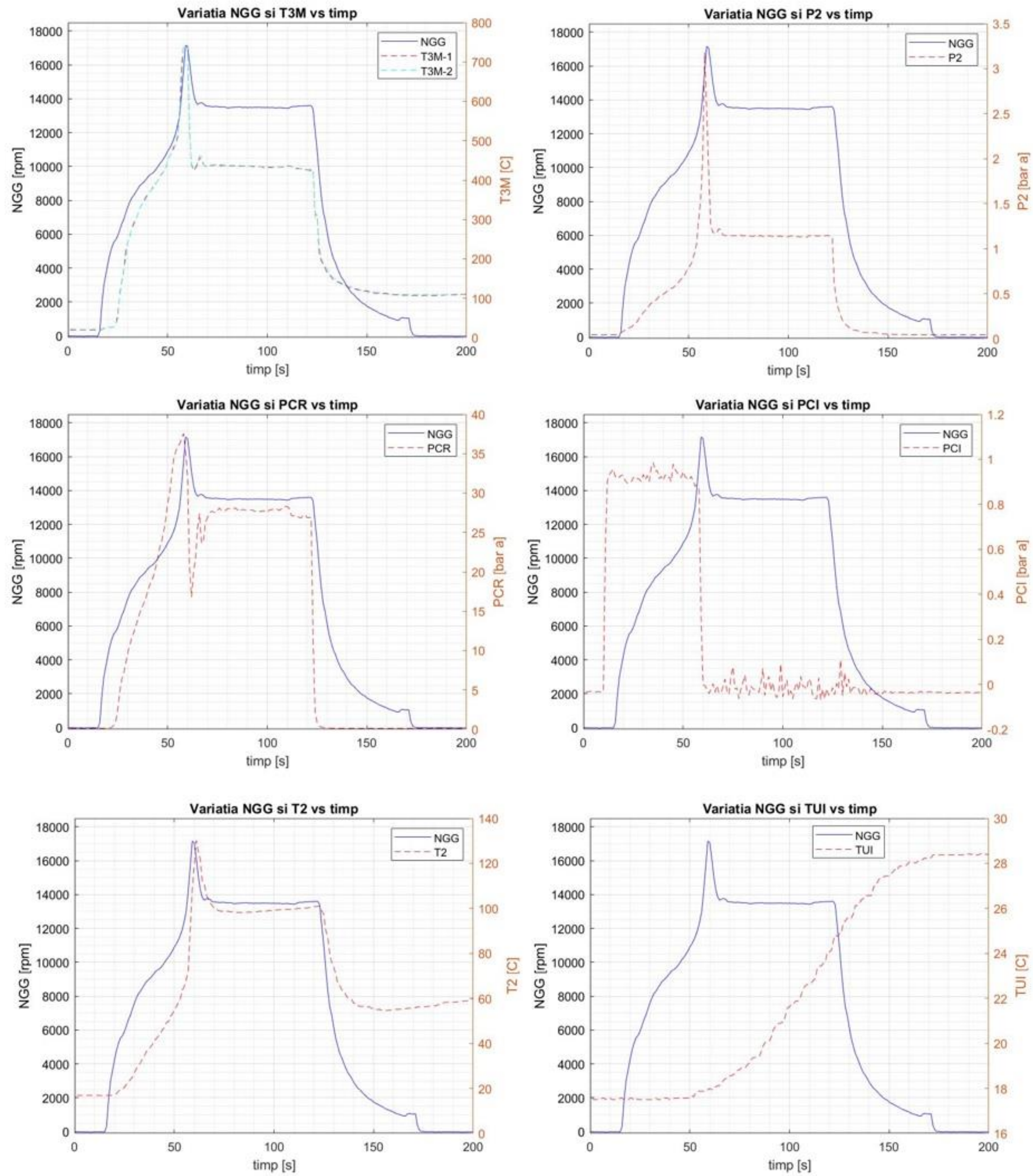


Figure 3.37. Average Combustion Chamber Temperature (T3M), After Compressor Pressure (P2), Ramp Fuel Pressure (PCR), Fuel Pressure (PCI), After Compressor Temperature (T2), Engine Inlet Oil Temperature (TUI) vs RPM gas generator (NGG) from Experiment No. 2

CHAPTER 4

LATEST GENERATION SOFTWARE USED IN AUTOMATIC REGULATION SYSTEMS PROGRAMMING FOR THE TEST AND EXPERIMENTATION BENCH

4.1.THE LABVIEW PROGRAMMING ENVIRONMENT AND ITS INTEGRATION IN THE AUTOMATIC REGULATION SYSTEM

The LabView software program [73] is a graphical programming environment, made by National Instruments, which offers a varied and high diversification of the way to acquire, process, save and manipulate data from the sensor to post-processing. It is used to develop automated production research, validation and testing systems. It represents one of the most used programming environments for testing gas turbines [74], rocket engines [75] and other specific applications due to its complexity in terms of monitoring and saving parameters, of the control system [76], of the vibration measurement system [77], but also of the creation of an interactive system between the operator and the operator interface [78]. It uses a series of additional modules that are used for more specific programming, for example the use of the "Vision Module" module for applications that include imaging devices, the "NI-Scope" module for applications that include devices oscilloscope type, etc.

This programming environment allows the creation of programs, called VI (virtual instrument file) through various methods, achieving the same goal. For example, acquisition of temperature-type parameters can be achieved by using a predefined VI called "DAQ Assistant", by correctly defining it using "DAQmx" elements, or by other methods.

To display the temperature, it is necessary to define the PLC channel, choose the related settings, select the acquisition time and acquire the raw waveform data.

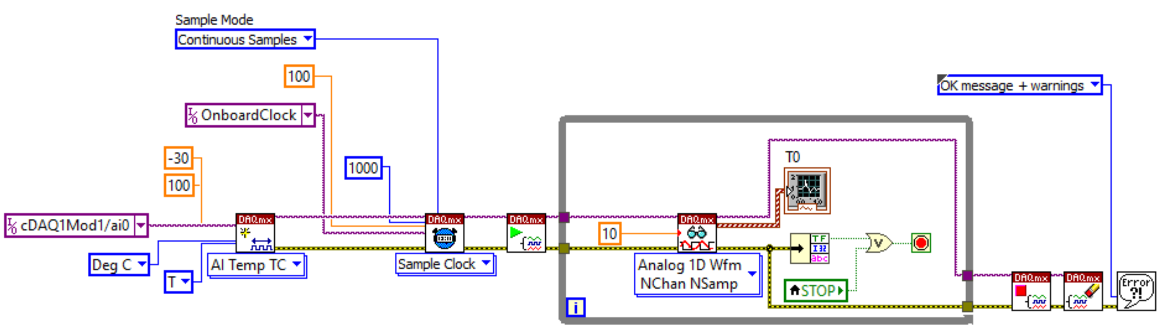


Figure 4.3. Defining the temperature reading channel and displaying the raw signal via DAQmx

4.2.REAL-TIME ALGORITHMS AND PROGRAMMING ENVIRONMENTS FOR REGULATION SYSTEMS

Real-time algorithms refer to programming in the LabVIEW environment for carrying out experiments or tests in a continuous environment that acquires certain parameters as input. Based on them, calculations of indirect parameters, which cannot be measured with sensors, transducers, or with special equipment, can be performed. Also based on the input parameters, links can be made with the output parameters, in the form of command and control, and any information is stored to perform the post-processing process and, where appropriate, the comparison with the theoretical counterpart.

4.3.AUTOMATIC REGULATION AND OPTIMAL CONTROL OF GAS TURBINE ENGINES USING A DEIDCATED SOFTWARE PROGRAM, CYRES

The CYRES program [45], made by the Safran Group, is a software program dedicated to gas turbine test cells through which parameters can be acquired, programs with command-and-control automation part can be created, native communication with other types of predefined PLCs can be made. It also communicates with video systems offered by Pelco [81] through a complex system. DACS ("Data acquisition and control system") has an architecture made up of several subsystems through which the tasks are divided in an efficient way, thus achieving increased performance and reliability.

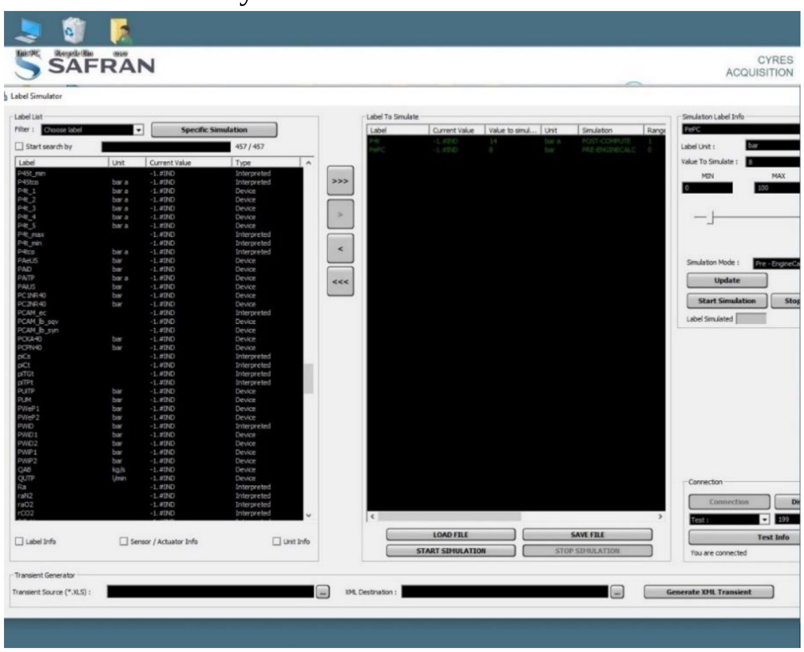


Figure 4.12. The algorithm made by "Engine Calculations" for determining the limitations in the emergency stop situation; Simulation and parameters verification in the data acquisition computer

The acquisition system can have a predefined rate of r_a=250 Hz and up to a maximum of r_a=100 kHz, with a compatible hardware system. It also uses a predefined part for testing and has advanced complexity for performing automated control.

Programming is done through several stages, having the assignment of models and tests according to the engine type that is specific for a series test. In Figure 4.13., an example of a CYRES made program is presented. The program works in real time for testing a gas turbine, including the instrumentation, command, control, automation and data saving steps.

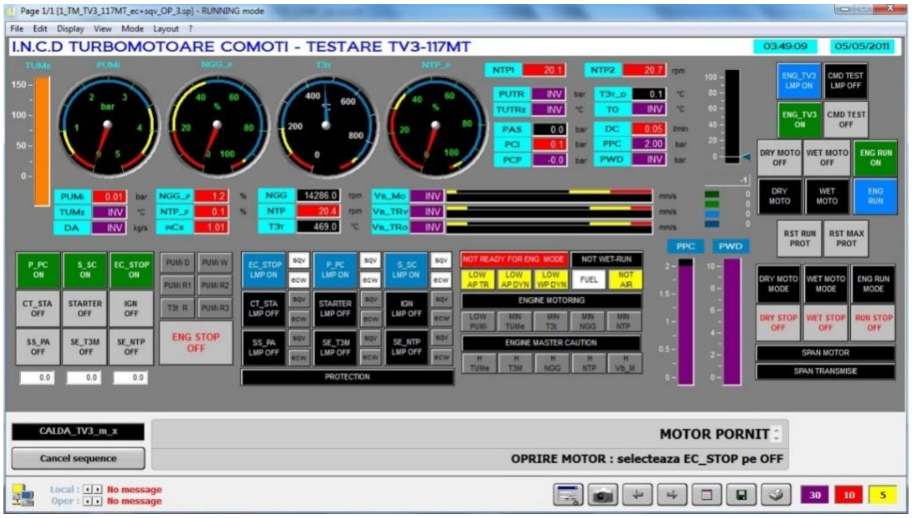


Figure 4.13. The operating panel for testing the gas turbine

For the post-processing part, a separate program is used and data has to be exported in a predefined table format.

4.4.MODERN ELECTRONICS IN CURRENT AUTOMATIC REGULATION SYSTEMS

Figure 4.14 shows an instrumentation prototype of a reaction nozzle, with the sensors arranged radially on the inside. They are connected in sets to five microprocessor and communication units (Gumstix Connex 400xm-bt boards with Bluetooth communication), mounted on the outside of the nozzle. The values from the sensors are transmitted wirelessly to a laptop station, on which the temperature map of the monitored area, profiles of the rate of temperature variation and, on request, the history of individual values are displayed. Similar to the thermal sensors, a smaller number of microphones were connected to demonstrate the possibility of adding a whole variety of sensors, as well as the possibility of working with high bandwidth sensors. Altogether, the wireless monitoring system contains: 20 IC temperature sensors with I2C interface, 4 microphones, 5 Gumstix-based processor nodes with custom expansion boards to provide audio and I2C connectivity, and the viewing laptop station.

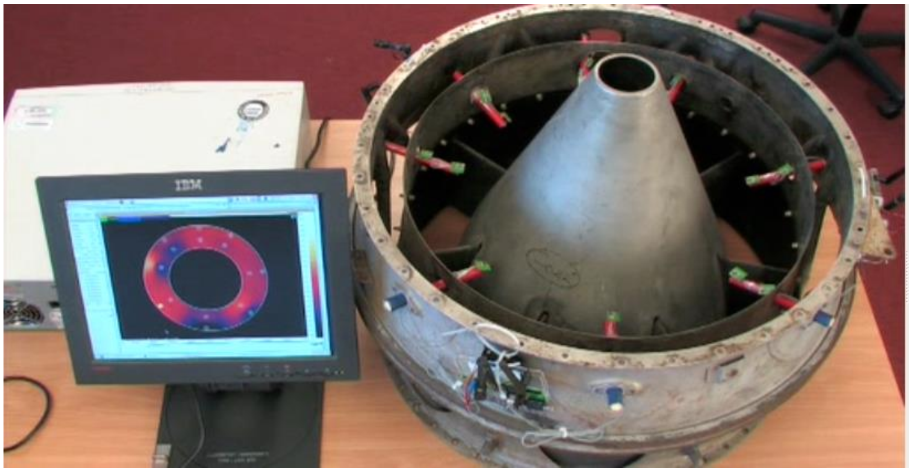


Figure 4.14. Feedback aid with prototype wireless instrumentation system [82]

4.5.DESIGN PROBLEMS OF ELECTRONIC AUTOMATIC REGULATION SYSTEMS

Physical contact (PC) connectors

They are the most widely used and have the lowest interface losses because the ends of the fibres touch and are designed not to lose contact once connected [84]. PC connectors include MIL-DTL-38999, which are the recognized standard for all military and commercial aerospace applications that depend on high performance and reliability. The 38999-connection system has been successfully used in applications such as the F-35 Joint Strike Fighter and the F-22 [85].

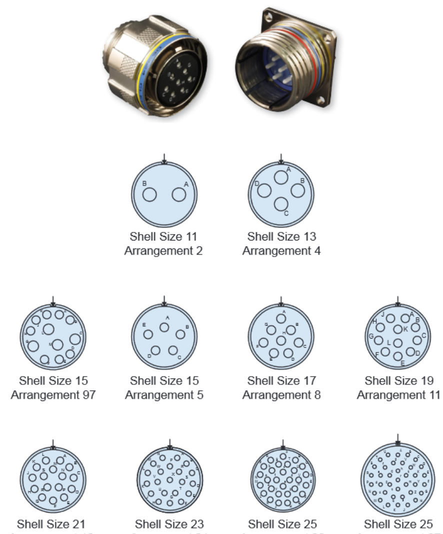


Figure 4.17. MIL-DTL-38999 connectors [86]

Typically, a PC connection is made by using a ceramic ferrule at the end of the optical fibre, fixed to the fibre by epoxy resin, and precisely polished so that light enters and exits with a known path and minimal loss [87].

CHAPTER 5

RESEARCH ON THE DEVELOPMENT AND REALIZATION OF AN AUTOMATIC REGULATION SYSTEM TO MEET THE CURRENT AVIATION ENGINE TESTING REQUIREMENTS

5.1. ESTABLISHING THE NECESSITIES AND DEVELOPING THE NEW AUTOMATIC REGULATION SYSTEM ARCHITECTURE RELATED TO THE NEW GAS TURBINE ENGINE REQUIREMENTS FROM AVIATION

The comparative study

- The automatic control system for the Solar-Centaur Onești gas turbine
  - Number of AI instrumentation lines: 40
  - Number of DO digital control lines: 33
  - Temperature measurement accuracy: 1 %
  - Pressure measurement accuracy: 0.25 %
  - Pressure probes response time: 100 Hz
  - Logic program running speed: 50 ms
  - Emergency stop loop response time: 66 ms
- The automatic control system for the ST40 Naval gas turbine
  - Number of AI instrumentation lines: 44
  - Number of DO digital control lines: 16
  - Temperature measurement accuracy: 1 %
  - Pressure measurement accuracy: 0.25 %
  - Pressure sensors response time: 500 Hz
  - Logic program running speed: 50 ms
  - Emergency stop loop response time: 66 ms
- The automatic control system for the ST18 Suplacu de Barcău gas turbine
  - Number of AI instrumentation lines: 58
  - Number of DO digital control lines: 33
  - Temperature measurement accuracy: 1 %
  - Pressure measurement accuracy: 0.25 %
  - Pressure sensors response time: 200 Hz
  - Logic program running speed: 35 ms
  - Emergency stop loop response time: 51 ms
- COMOTI automatic control system
  - Number of AI instrumentation lines: 64
  - Number of DO digital control lines: 11
  - Temperature measurement accuracy: 1 %
  - Pressure measurement accuracy: 0.25 %
  - Pressure sensors response time: 100 Hz
  - Logic program running speed: 20 ms

• Emergency stop loop response time: 36 ms

Following the analysis and research carried out on several automatic regulation systems both in industrial installations that use aviation gas turbines and in stands specially set up for testing these types of engines, we established the requirements for the new automatic regulation system considering the current requirements for testing gas turbines but also their complexity:

- Number of instrumentation lines = AI 112 / AO 16
- Number of digital command lines = DI 32 / DO 32
- Accuracy of pressure measurement sensors = 0.04 % of the maximum measurement range
- The response time of the pressure measurement sensors = 3500 Hz
- Accuracy of data acquisition modules = 0.01 % of maximum range
- Response speed of data acquisition modules = 100 kHz per channel
- Information to be processed on several computers;
- Allow the Ethernet connection with Scanivalve MPS4264 and the ANET - ARINC429 card;
- To have a second safety PLC used strictly for the protection and safe shutdown of the tested gas turbine in the "Master-Slave" type configuration;
- The response time of the stop safety line loop should be less than 20 ms;
- The execution speed of the data acquisition and control loop should be less than 50 ms;
- The acquisition speed for all parameters can reach a maximum of 10 kHz;
- Compact, mobile system with a UPS power supply unit to power the system for at least 15 minutes from the occurrence of a fault on the power supply line.
- Determination of the transfer functions for the emergency stop line and realization of the new architecture of the proposed automatic regulation system.

The determination of the transfer functions is based on the specialized literature [92-94] and aims to determine the control functions for the emergency stop system.

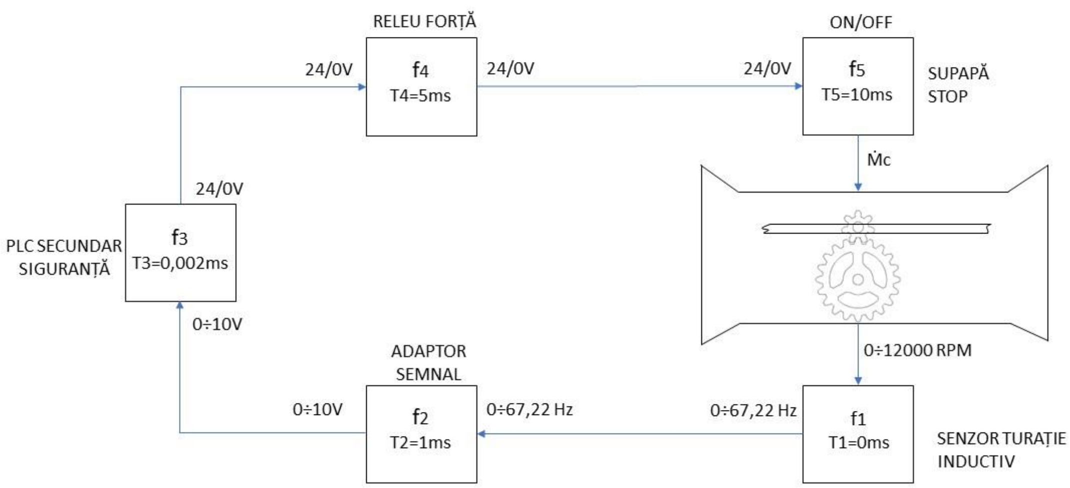


Figure 5.2. Block diagram of emergency stop line by NTP speed parameter

Determination of the transfer function for the inductive speed sensor:

Transmission ratio Z=0.3361

The output frequency is F_i

$$F_i = f(N) \tag{5.1}$$

$$F_i = \frac{N}{60} \cdot z \tag{5.2}$$

If$N = 12000\, rpm$

$$F_i = \frac{N}{60} \cdot 0.3361 = 67.22\, Hz \tag{5.3}$$

A linear function is considered:

$$f(x_1) = a_1 x_1 + b_1 = f_1 \tag{5.4}$$

Where

$$a_1 = \frac{Z}{60} = \frac{0.3361}{60}\ și\ x_1 = N \tag{5.5}$$

$$f_1 = \frac{Z}{60} \cdot N + b_1 \tag{5.6}$$

$$f_1 = 67.22 + b_1 \tag{5.7}$$

Then

$$f_1 = F_i \rightarrow b_1 = 0 \tag{5.8}$$

Determination of the transfer function for the analogue signal converter:

The signal converter has a linear variation through boundary conditions and the coefficients $a_2$and $b_2$have been calculated.

The values are based on the following scheme: input signal (*x*) – output signal (*y*)

$$0\, Hz \rightarrow 0\, V \tag{5.9}$$

$$67.22\, Hz \rightarrow 10\, V \tag{5.10}$$

A linear function is defined:

$$f(x_2) = a_2 x_2 + b_2 = f_2 \tag{5.11}$$

Resulting:

For $x = 0$and$y = 0$

$$a_2 \cdot 0 + b_2 = 0 \rightarrow b_2 = 0 \tag{5.12}$$

For $x = 67.22$, $y = 10$ și $b_2 = 0$

$$a_2 \cdot 67.22 + b_2 = 10 \rightarrow a_2 = \frac{10}{67.22} = 0.148765 \quad (5.13)$$

Determination of the transfer function for safety PLC:

The output signal from the safety PLC is step-type. The "Heaviside" function is used to determine the transfer function. The Heaviside step function, or unit step function, usually denoted by H or is a step function, whose value is zero for negative arguments and one for positive arguments. It is an example of the general class of step functions, all of which can be represented as linear combinations of its translations. The function was originally developed in operational calculus for solving differential equations, where it represents a signal that turns on, at a specified time and remains on indefinitely.

$$H(x) = \begin{cases} 0, & x < 0 \\ 1, & x \geq 0 \end{cases} \quad (5.14)$$

The values are based on the following scheme: input signal (*x*) – output signal (*y*)

$$0\,V \rightarrow 24\,V \quad (5.15)$$

$$10\,V \rightarrow 0\,V \quad (5.16)$$

Resulting:

$$f(x_3) = a_3 H(b_3 x_3 + C_3) = f_3 \quad (5.17)$$

$$f_3 = H(10 - V) \cdot 24 \quad (5.18)$$

$$C_3 = 10 \quad (5.19)$$

For $x = 0$ și $y = 24$

$$a_3 H(b_3 \cdot 0 + C_3) = 24 \quad (5.20)$$

$$a_3 H(C_3) = 24 \quad (5.21)$$

$$a_3 = 24 \quad (5.22)$$

For $x = 10$, $y = 0$, $a_3 = 24$, $C_3 = 10$

$$24 \cdot H(10 \cdot b_3 + 10) = 0 \rightarrow H(10 \cdot b_3 + 10) = 0 \rightarrow (10 \cdot b_3 + 10) = 0 \quad (5.23)$$

$$b_3 = -1 \quad (5.24)$$

Determination of the transfer function for the Force Relay:

The relay is an On/Off device, used to determine the transfer function. An identity function I was used as follows.

$$f(x) = x = I(x) \quad (5.25)$$

The values are based on the following scheme: input signal (*x*) – output signal (*y*)

$$0\,V \ \rightarrow 0\,V \tag{5.26}$$

$$24\,V \ \rightarrow 24\,V \tag{5.27}$$

The equivalent form that can be used is:

$$f(x_4) = a_4 x_4 + b_4 = f_4 \tag{5.28}$$

For$x = 0$and$y = 0$

$$a_4 \cdot 0 + b_4 = 0 \rightarrow b_4 = 0 \tag{5.29}$$

For $x = 24$, $y = 24$and$b_4 = 0$

$$a_4 \cdot 24 + b_4 = 24 \rightarrow a_4 = 1 \tag{5.30}$$

Determination of the Transfer Function for the Stop Valve:
The stop valve is a 2-state closed/open (Off/On) execution equipment.
The values are based on the following scheme: input signal (x) – output signal (y):

$$0\,V \ \rightarrow 0 \tag{5.31}$$

$$24\,V \ \rightarrow 1 \tag{5.32}$$

The following form of the transfer function can be considered:

$$f(x_5) = a_5 x_5 + b_5 = f_5 \tag{5.33}$$

For $x = 0$ și $y = 0$

$$a_5 \cdot 0 + b_5 = 0 \rightarrow b_5 = 0 \tag{5.34}$$

For $x = 24$, $y = 1$ și $b_5 = 0$

$$a_5 \cdot 24 + b_5 = 1 \rightarrow a_5 = \frac{1}{24} = 0{,}041(6) \tag{5.35}$$

- Designing the general transfer function

The general form is defined as:

$$F = f_5\left(f_4\left(f_3(f_2(f_1))\right)\right) \tag{5.36}$$

The explicit form of the general transfer function

$$F = f_5\left(f_4\left(f_3(f_2(a_1 x_1 + b_1))\right)\right) \tag{5.37}$$

$$F = f_5\left(f_4(f_3(a_2(a_1 x_1 + b_1) + b_2))\right) \tag{5.38}$$

$$F = f_5\big(f_4(H(a_2(a_1x_1 + b_1) + b_2) + b_3)\big) \quad (5.39)$$

$$F = f_5(a_4(H(10 - (a_2(a_1x_1 + b_1) + b_2) \cdot 24) + b_3)) \quad (5.40)$$

$$F = f_5\big(I(H(a_3(a_2(a_1x_1 + b_1) + b_2) + b_3)\big) \quad (5.41)$$

$$F = a_5\big(I(H(a_3(a_2(a_1x_1 + b_1) + b_2) + b_3)\big) + b_5 \quad (5.42)$$

$$F = a_5(a_4(a_3 \cdot H(a_2(a_1x_1 + b_1) + b_2) + b_3) + b_4) + b_5 \quad (5.43)$$

$$F = a_5(a_4(a_3 \cdot H(b_3(a_2(a_1x_1 + b_1) + b_2) + C_3)) + b_4) + b_5 \quad (5.44)$$

Determining the delay time of the emergency stop loop:

The delay time is denoted by T_i

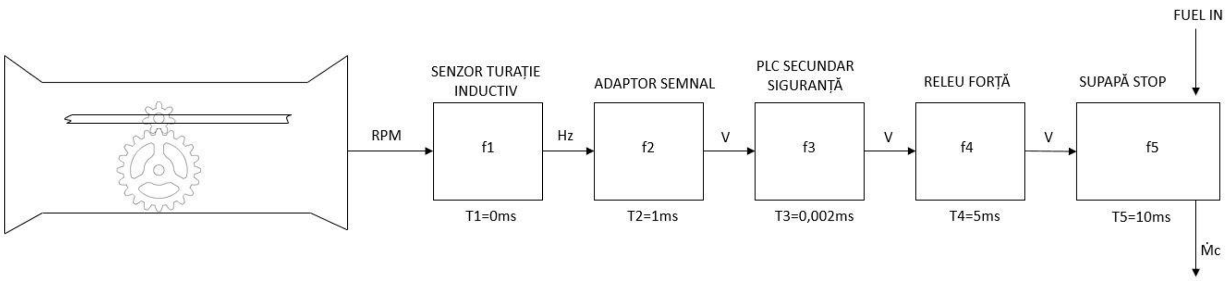


Figure 5.5. Logic diagram regarding delay times

$$T_i = t_1 + t_2 + t_3 + t_4 + t_5 \quad (5.67)$$

Where:

- $t_1 = 0\ ms$ and represents the delay time of the speed sensor,
- $t_2 = 1\ ms$ and represents the delay time of the signal converter,
- $t_3 = 0.003\ ms$ and represents the delay time of the safety PLC,
- $t_4 = 5\ ms$ and represents the delay time of the electronic force relay,
- $t_5 = 10\ ms$ and represents the delay time of the stop valve.

It results that: $T_i = 16.003\ ms$ (5.68)

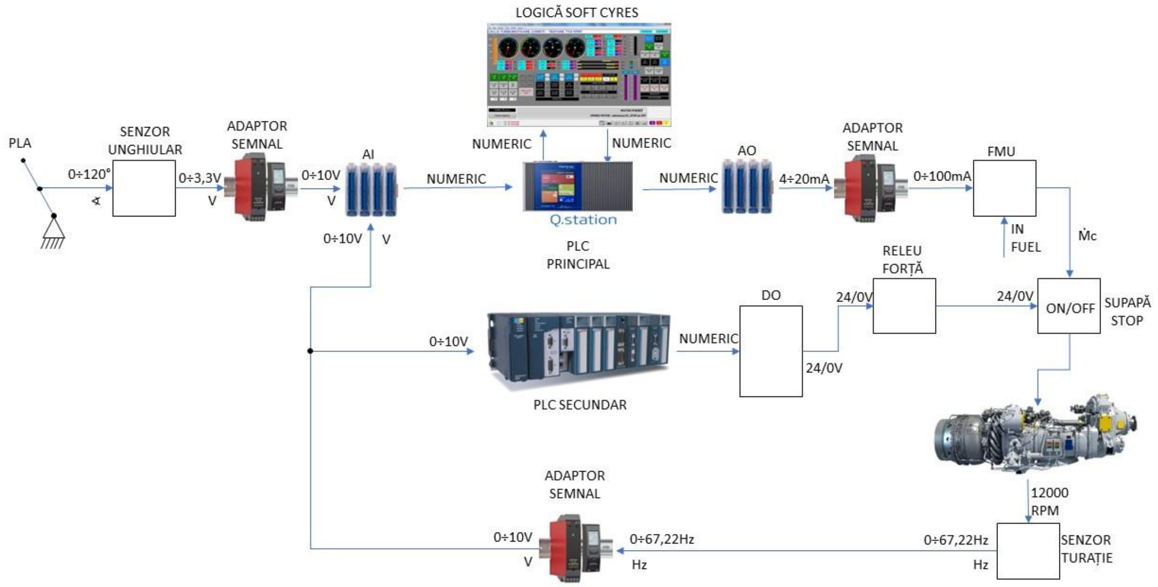


Figure 5.6. Block diagram for the mode regulation line together with the feedback and the NTP emergency stop line separated by a secondary safety PLC

5.2. ANALYSIS OF THE EQUIPMENT USED IN THE AUTOMATIC REGULATION SYSTEM FROM THE PERFORMANCE CHARACTERISTICS POINT OF VIEW

Qstation Gatner programmable automaton

The Qstation programmable controller [95] is the interface between the Qseries modules and the connected host/automation system (PC or PLC) and thus becomes a data acquisition and a control system. The main functions of the controller are to ensure the synchronization of measurement data from several Qseries modules, the buffering and conditioning of that data and the transmission of data to the host/automation system via Ethernet, Profibus, CANopen, EtherCAT or other supported protocols. Several controller options are available to support systems of all sizes and levels of complexity. By separating the controller from the measurement modules, communication is significantly optimized (only a "slave" for the PC or PLC unit). The range and flexibility of the modules enable an optimized solution for each unique task: dynamic signal acquisition up to 100 kHz, inputs/outputs for all signal types, galvanic isolation of inputs/outputs, multi-channel solutions, high-density packaging and intelligent signal conditioning.

Figure 5.11. Data acquisition and control system consisting of Q.station and Q.series

Among the most important technical specifications are:

- The controller supports up to 64 connected Q.bloxx modules of any type;
- It allows a high acquisition rate depending on the number of defined channels, for 16 channels the maximum rate is 100 kHz, for 128 channels the maximum rate is 10 kHz;
- Data synchronization in time and the time parameter for measurements is of the IRIG 2 type, based on a main "master", connected with RS485 through a standard synchronization system with a precision of ± 1 μs but with the possibility to integrate through other types, such as GPS with NMEA type via RS-232/Usb, Time Server with SNTP type via ethernet or distributed clock with DC type via EtherCAT;
- It has a wide memory bandwidth, in a dynamic environment of 500 MByte and in a static environment of 4 GByte, with the possibility of expansion via USB (up to 1,000,000 measurements/s);
- The controller has a number of 8 channels of digital inputs, used for configurable counter, frequency, PWM and digital encoders with status signals focusing with synchronous angle measurement, but also a number of 4 channels of digital outputs, configurable function of type " watchdog" but also for emergency use in case of breakdown;
- Extended library PAC functionality (only for certain controller variants) including: fast PID ("Proportional-Integral-Derivative") controllers, process control, data logging, transfer functions, mathematical relationships, "Boolean" combinations, function generators;
- It is programmed through the dedicated software "test.commander", but also through the use of other types of software, such as test.viewer, test.node, test.con Studio, or specialized data acquisition programs: LabVIEW, DIAdem, Matlab and Simulink, DASYLab, MSCPP60, MSVBasic60, DELPHI2006. The test.viewer program performs the process of viewing and storing data in numerical or graphical format and converting

data into formats such as: GreenEye (*.ged), DASYLab (*.ddf), Famos (*.dat), MATLAB (*.mat), Bernard (*.bbl), WAVE (*.wav) and Excel (*.csv). The test.node program not only performs the part of storing the data on local desktop drives, on the network or in databases, but alsooffers the possibility to configure the settings for the save process.

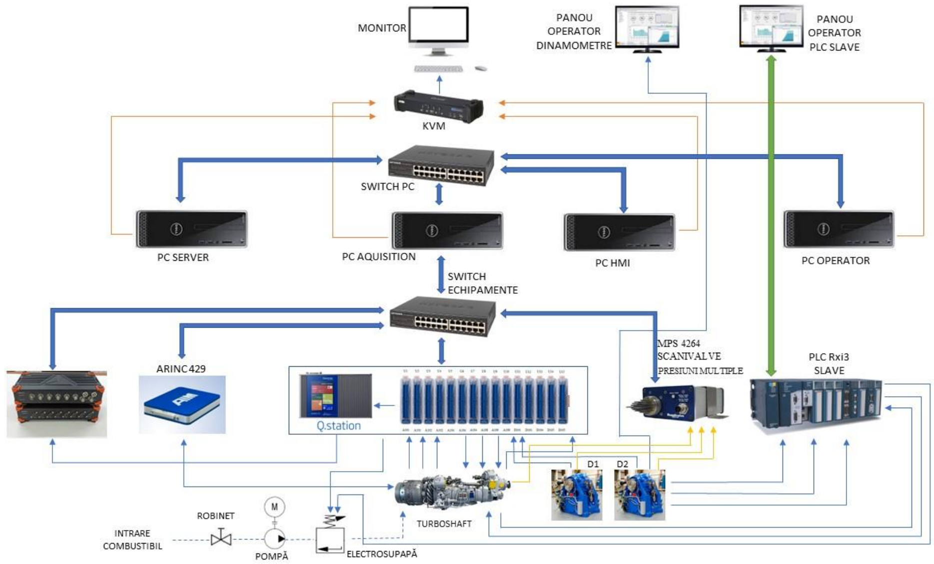


Figure 5.9. Block diagram of the system used in the configuration for engines with turboshaft

5.3. INSTRUMENTATION BLOCK DIAGRAM OF THE GAS TURBINE ENGINES AND AUXILIARY DATA ACQUISITION SYSTEM

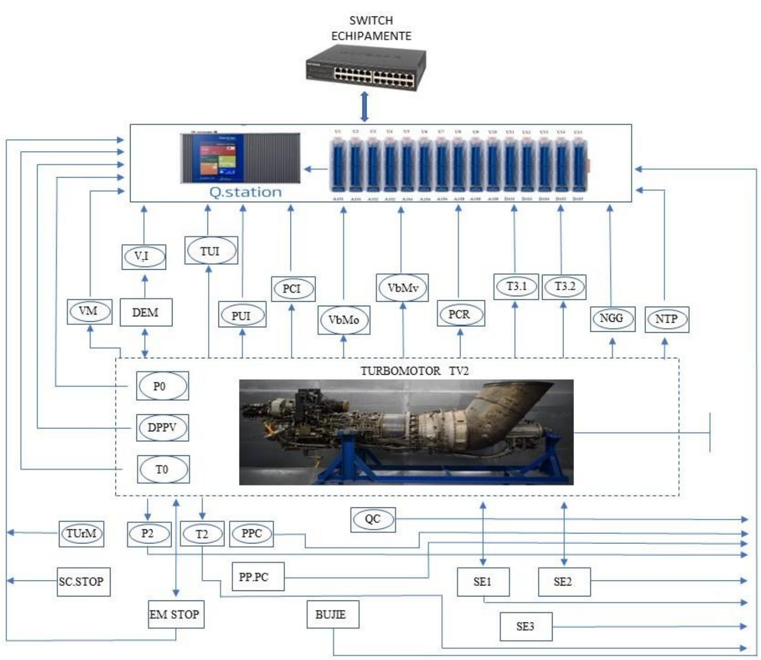


Figure 5.35. Instrumentation, command and control diagram for the TV2-117A gas turbine

5.4. ANALYSIS OF THE CAPABILITY OF THE REGULATION SYSTEM FOR THE PROPOSED TEST BENCH

Based on the block diagrams, the automatic regulation system was created,

Figure 5.37. Fully automatic control system

Monitoring and the controlling of the gas turbine are carried out from the control room, shown in Figure 5.33 together with monitoring and controlling of the necessary auxiliary systems. It can be seen how the lever represents a separate aggregate, which performs the direct command of the gas turbine control.

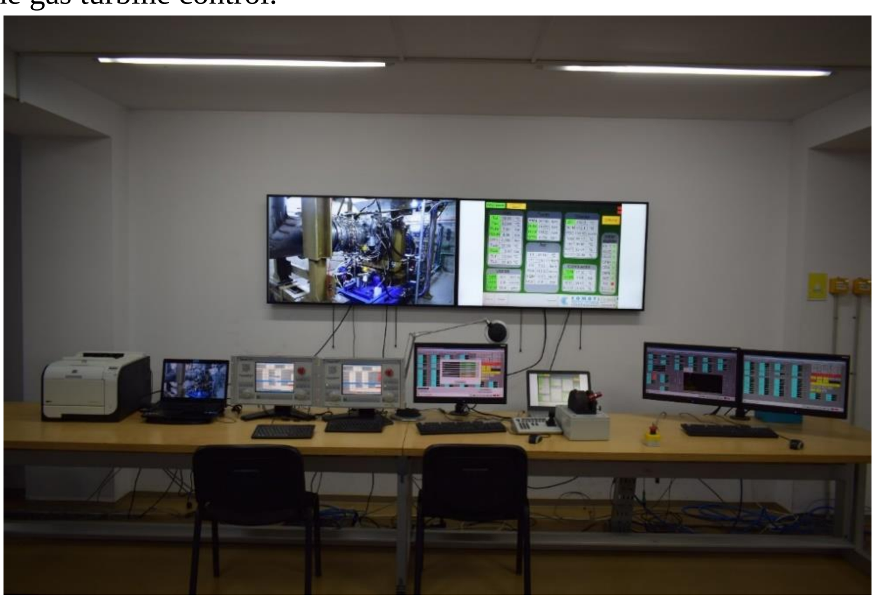


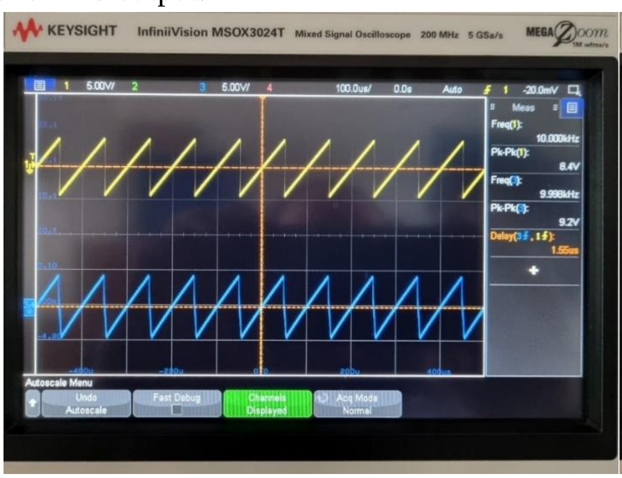
Figure 5.38. Control room for the proposed regulation system

- The loading and torque measurement systems with HS2600 dynamometers

The Froude Hofmann HS2600 hydraulic dynamometer [114] is rated at 2,600 kW (3,490 hp) and has a maximum operating speed of 24,000 rpm, with continuous overshoot capability up to 26,500 rpm. The HS range of dynamometers is designed to test industrial and marine gas and steam turbines and aircraft gas turbine modules testing in many applications including research and development, production and overhaul. The HS range covers outputs from 1,865 kW to 14,915 kW (1,210 BHP to 20,000 BHP) in one direction of rotation. To accommodate for counter-rotating engines, the dynamometers are fitted with two coupling halves and can be rotated 180° either with the crane or with an optional pneumatic turntable.

- Testing the regulation system with different types of input and output signals

Since we could only consider the equipment specifications because other Ethernet communication constraints also intervene, we resorted to determining the response time for the Rxi3 secondary safety PLC, by simulating several signals, such as the ramp, sinusoidal and step signal. The measurements were made with a last-generation oscilloscope that can measure signals with a frequency of up to 200 MHz. The resulting delay times were less than 3 μs, so a delay time of 3 μs was calculated for this communication line PLC input, PLC signal processing and PLC output.



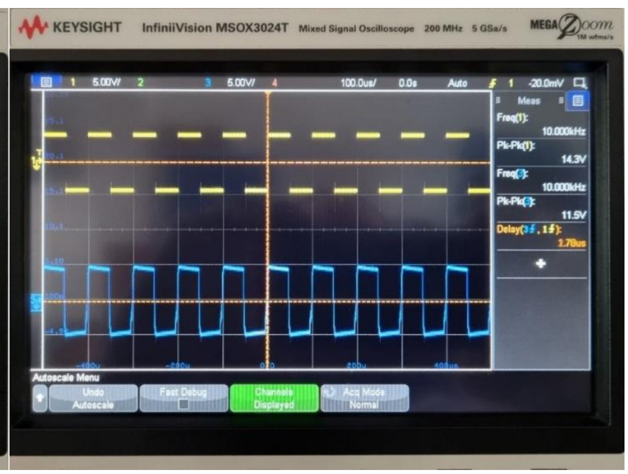


Figure 5.40. Ramp signal simulation Figure 5.42. Step signal simulation

5.5. EXPERIMENTATION AND DATA ANALYSIS OBTAINED WITH THE PROPOSED REGULATION SYSTEM

The reference gas turbine TV2-117A

For testing in the test cell, the reference gas turbine was mounted with mechanical support, assemblies and ducting for the air intake and exhaust area. Also, a basic instrumentation was made, according to the technical manual of the engine [20], that incorporates sufficient number of thermogasodynamic parameters, which were linked with the command-and-control elements.

5.6.COMPARATIVE DATA ANALYSIS BETWEEN THE OLD SYSTEM AND THE PROPOSED SYSTEM

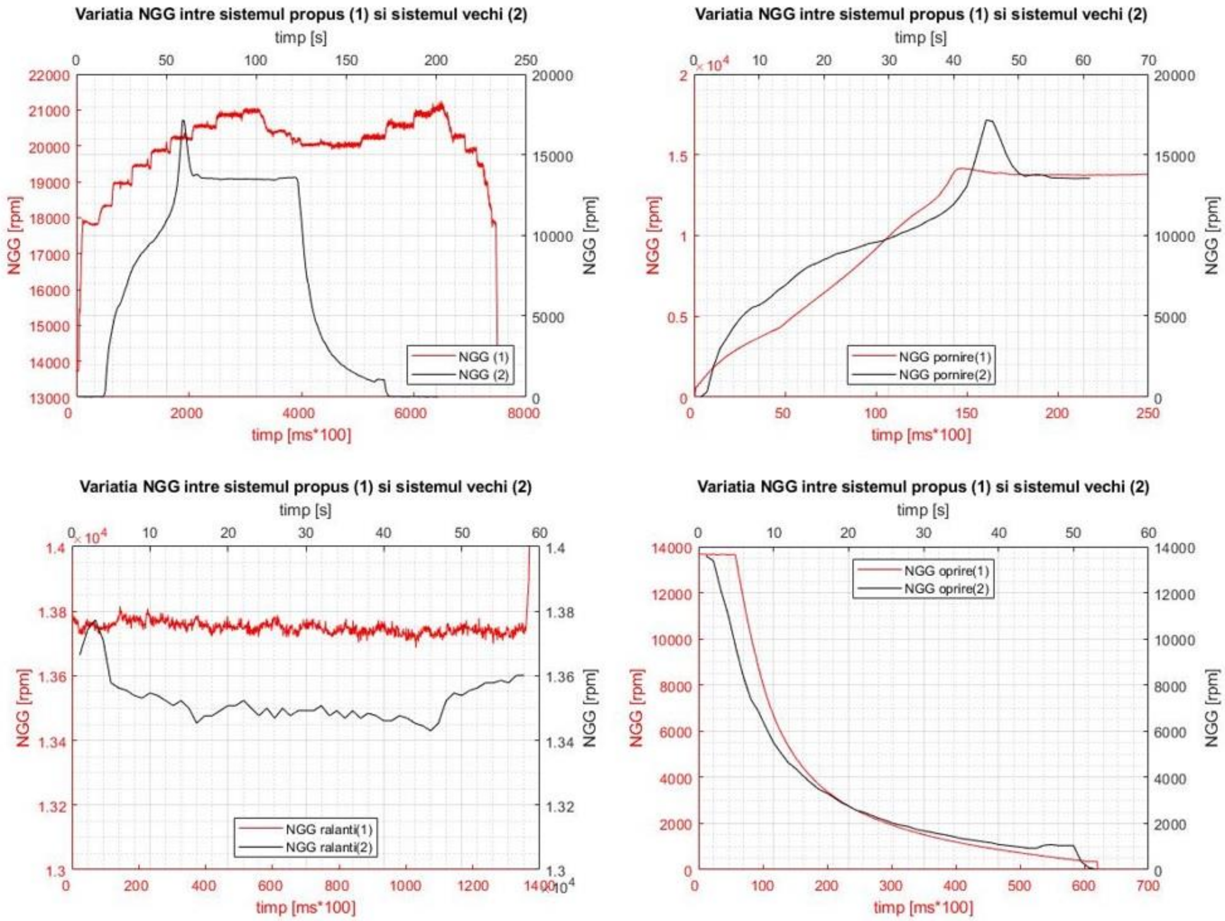


Figure 5.51. Data comparison between the proposed system (1) and the old system (2)

Analyzing the graphs of both experiments, for the NGG parameter at several operating regimes, it is observed the high stability in the idle output control, the accuracy through the multitude of acquired points and that the speed is much higher than in the previous test. It can also be seen not only a better stability of maintaining the control at idle speed, much smaller variations and much smoother stop curve, but also that there are no jumps or variations in the rpm reading.

CONCLUSIONS

In the present paper, a comparative study of several automatic regulation systems found in several types of gas turbines, from older generation to the latest generation, were presented, with the aim of determining the drawbacks and analyzing some key components to be able to find ways to improve and adapt these automatic tuning systems, in order to reduce the response time for several lines of safety instrumentation, to increase the frequencies of given acquisitions for several important gas turbine parameters such as: pressure and vibration and to integrate a new equipment to monitor the evolution of certain essential parameters, such as the turbine speed, being able to stop the gas turbine under test very quickly, in conditions of maximum safety.

Based on the study of several automatic fuel metering systems, their block diagrams were determined to better understand the step-by-step evolution and changes they underwent over time, and the operation mode of each system, pointing out the advantages and disadvantages, while analyzing various methods of their improvement. By presenting the block diagrams of different aviation gas turbines, from different periods, it is observed an increase in the number of aggregates, an increase in the number of equipment necessary for the best possible control of the entire gas turbine and an increase in the number of parameters that are considered in the calculation for regime regulation.

It was aimed to present as clearly as possible the theoretical side of the automatic regulation systems and the regulation of gas turbines by stating the basic notions, the introductory notions, touching all the points from the start of an aviation gas turbine, to acceleration and to reaching the maximum regime and the afterburn regime, but also the definitions of the main elements that make up the automatic regulation systems, in order to understand very well how the blocks are interconnected together and how gas turbines work and what are the working regimes, so that, at the exit from the regulator block, to obtain the signal of desired fuel flow for the selected regime.

Today's modern systems use digital electrical signals converted from analogue signals on multiple transmit/receive Tx/Rx channels. This method is not only redundant and provides a "backup" for the communication lines, but also provides a very high, almost instantaneous speed of data transmission compared to mechanical or hydraulic systems of the past, where there were delays in the transmission of information and from the movement of the throttle lever to the actual increase in the engine speed. For the engine under test there is a delay of about 1-2 seconds.

Over time, the evolution of aviation engines, in terms of constructive configuration (twin-flow turbojet engine, single-flow turbojet engine, single-rotor, bi-rotor, tri-rotor, variable pitch), it has been determined that the requirements for automatic regulation become more and more complex and that they take into account more regulation factors, which also increases the processing time of real-time situations.

Specialized software exhibits feature specific to the nature of the application. The CYRES program is strictly dedicated to testing turbo-engines and turbo-fans and is among the most suitable for this. It allows communication with a wide range of PLCs and equipment to perform the testing process according to standards.

The LabVIEW program presents a higher complexity, mainly due to the programming method that starts from the definition of the PLC to the real-time processing of the data and is recommended for various specific applications and also for the testing of micro gas turbines.

For auxiliary systems, Proficy Machine Edition is used through ladder-type programming ("LAD") due to its reduced programming complexity and increased reliability. There are also dedicated vibration measurement programs such as Dewesoft which allow reading accelerometers, speedometers, and proximity parameters at a very high acquisition rate and across the frequency spectrum to detect any inconsistencies.

The FADEC system is, at present, the most advanced automatic control system for gas turbines that equip the aircrafts and for the bench testing of the aviation gas turbines. An intelligent automatic control system is also used and is capable of completely governing the test program but it can be improved by using state-of-the-art electronic equipment and integrating it at key points to make certain safety decisions faster compared to human response time.

This equipment has evolved from mechanical equipment to hydromechanical equipment then to pneumatic equipment, to electromechanical equipment and finally to electronic equipment.

Electronic equipment, bringing a significant number of advantages such as: reducing the weight of the entire gas turbine, simplicity in the actuation of the dosing elements, measuring several important parameters with high acquisition speed, much faster management of the equipment receiving orders and much faster decision making than the human factor due to the implementation of the software program and the response characteristics of the equipment.

The new architectures of the automatic regulation systems will have to take into account the complexity of the requirements imposed by the manufacturers of gas turbines and turbofans, both on the hardware side and on the software side, and will have to align with the current logic programming trends, that have become more and more complex and at the same time more intuitive, using dedicated software where G-type graphic programming is used.

The architecture of the data acquisition system is highlighted. This consists of a single PLC, which has the role of receiving information from sensors, transducers, equipment, processing said information and convert it into the actual measurement units and give commands when appropriate at the same time. For these reasons, it become required during a test.

At the same time, the PLC GE 90-30 also presents some limitations such as, reduced number of supported modules, reduced number of channels in the respective modules and a relatively low measurement accuracy. For the system realized with only a PLC unit, the equipment, sensors and transducers used are part of the previous generation, have strictly analogue communication and do not have the ability to communicate digitally. Accuracy and sensitivity are at a lower level with higher errors for a more precise measurement process.

The acquisition system was made based on electrical diagrams and based on technical manuals with equipment, sensors and transducers. Signal shielding was also considered to eliminate as much as possible all external disturbances, but also to protect the modules with electrical fuses.

The stand's capability consisted in instrumenting the engine, ensuring optimal operating conditions through auxiliary systems, but engine testing was only performed at idle speed due to the lack of a hydraulic braking system through a dynamometer system and thus it was necessary to block the free turbine.

The adapted automatic control system realized in the multi-computer configuration for information processing, with a state-of-the-art main PLC to acquire all the signals from all the sensors very quickly, sending this information to the acquisition computer called "ACQ" which handles of the management of the links between the sensors and the parameters and then the computer for the management of the logic software, together with a secondary PLC used strictly for the monitoring of the speed and the emergency stop, this variant being the fastest at the moment, together with very precise acquisition modules and with high response speed, managed to reach the level of the requirements imposed following the analysis of other automatic regulation systems, eliminating as much as possible disturbances, program errors, increasing precision, acquisition speed and reducing response times to as low as possible, managed to control the TV2-117A gas turbine much more stably at all regimes d it's working.

The conclusions provide a complete picture on the work and on the regulation, on the systems realized up to the present moment, with highlight of the disadvantages and weak points that they have, the establishment of the requirements and the equipment for the new system, the determination of the performances obtained by the new regulation system, especially on the stop line emergency, which is also an element of novelty. Data comparison obtained from experiments with a system but with a different configuration is presented. The advantages of the new automatic regulation system are highlighted to point out the original contributions made to this system, but also future development perspectives.

The final conclusion of the doctoral thesis herein revolves around the implementation of new emerging technologies and the adaptation of an automatic control system, on the test stand, capable of meeting the current requirements imposed in the testing of gas turbines, which can manage as many parameters of the gas turbine as possible, being able to intervene on some constants in real time, without disturbing the functionality.

ORIGINAL CONTRIBUTIONS

- The architecture of the automatic regulation system that uses acquisition equipment for electrical signals but also dedicated desktop units for each subsystem, thus reducing the flow of data processed on a single processor;
- Logic programming and information processing on several computers that allows independent programming of subsystems, such as data acquisition, parameter measurement lines, code lines for control and test logic and in addition data saving and processing that can be programmed independently, thus simplifying and using the data flow as efficiently as possible;
- The introduction of a second monitoring PLC to increase safety in gas turbine testing, it will acquire several important parameters separately, it will continuously analyze them and deciding by itself when to stop the gas turbine tested in the test bench;
- Using the best equipment in the field with a very high acquisition rate of 10kHz and suitable for the testing requirements;
- Using the Ethernet communication bus in the current architecture to connect other equipment to the fast data acquisition system, such as: ANET 429 and Scanivalve MPS4264;
- The use of ANET mode which can communicate with FADEC units on certain engines, thus facilitating integration into the automatic tuning system of the test stand of the latest engines using such systems.
- Increasing the speed of data acquisition by using digital communication up to 10 kHz.

PROSPECTS FOR FUTURE DEVELOPMENT

- Increasing the acquisition rate of parameters above 10KHz using a 2nd PLC Qstation thus dividing the slow signals coming from certain sensors, from the fast signals coming from the high-speed sensors used in key areas for important parameters. that will be acquired very fast, showing with high fidelity the evolution of the physical phenomenon;
- The use of electronic execution elements, without mechanical parts, the elimination of classic switching relays;
- Use of acquisition modules with Wi-Fi communication for remote testing;
- The use of electronic and independent fuel regulators for regulating the fuel flow as elements of execution on the engine;
- Eliminating mechanical or hydraulic actuation from the engine and using electronic actuators to perform a study at several operating regimes of the gas turbine.

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Patents and patent applications:

1. Cerere de brevet, „*STAND MOBIL DE TESTARE ROTORI DE VENTILATOR CONTRAROTATIVI*”https://osim.ro/wp-content/uploads/Publicatii-OSIM/BOPI-Inventii/2021/bopi_inv_07_2021.pdf
2. Brevet nr. 133517, *„STAND MOBIL DE TESTARE A VENTILATOARELOR PENTRU MOTOARE TURBOFAN”*, 2021http://pub.osim.ro/publication-server/pdf-document?PN=RO133517%20RO%20133517&iDocId=12198&iepatch=.pdf