EMBEDDED DEVELOPMENT SYSTEM FOR GAS TURBINE IDENTIFICATION PROCESS

Károly BENEDA*
AEROK Aviation Technical Training Centre Ltd., H1191 Budapest, Üllői út 200. Hungary
Ladislav FŐZŐ
Department of Aviation Engineering, Technical University of Košice, Rampová 7, Košice, Slovakia
**Corresponding author.* E-mail: karoly.beneda@aerok.eu

Summary. Embedded microcontroller systems are emerging in various fields of industry that offer versatile connection possibilities with real world equipment. They offer powerful computational capacity; they incorporate different analog inputs to acquire proportional parameters; their analog outputs that can be used to generate time-varying signals; digital inputs and outputs can measure and control parameters having two states. These development systems also have significant literature about different communication protocols to interface them with commercial computer systems. In gas turbine development they can be used efficiently in various roles due to the wide variety of their capabilities. In the present article the authors present a possible utilization of the mbed LPC1768 prototyping system for the identification process of gas turbine engines. In order to measure the time and frequency domain characteristics of the engine the circuit has been configured in both hardware and software to accept and generate signals respected to the gas turbine. This paper the authors detail the build-up and show results of measurements conducted with the created embedded system.

Keywords: gas turbine engine, turbojet engine, embedded development system, mbed LPC1768, system identification

1. INTRODUCTION

Gas turbines form an important power source for various industrial applications including power generation from micro- [1] to large scale [2], and airborne transportation [3]. Turbojet engines have nowadays a reduced share [4], but they still can be found in different roles like military unmanned aerial vehicles [5], in sailplanes as auxiliary thrust generation [6] and they can be used in education as well [7]. Their operation can be modeled in different ways depending on what is the depth that the mathematical model should have [8]. The researcher must decide which model suits the actual demands of the development. As the goal is to create a control system in the future, at this step the authors have chosen the black-box approach, which significantly reduces the complexity of the model.

The evolving information technology enabled a significant progress in aviation industry including development of power plant systems. These include e.g. CAD or Computational Fluid Dynamics (CFD) methods that allow virtual prototyping [9] or one can consider small electronic devices as the basis for Full Authority Digital Electronic Control (FADEC) systems, that can monitor plenty of engine related signals to optimize performance, they also reduce crew workload by allowing more automatic operation and establish more economic utilization of the unit by providing comprehensive diagnostic functions, among many others [10]. Therefore the development of automatic control systems is very important and should be assisted by enhanced devices and methods as well.

The intent of the authors is to present a solution in this article for gas turbine system identification using up-to-date electronic aid in the form of an embedded development system. The description focuses on the transfer function of the plant between fuel metering valve control voltage as input to the system and the rotor speed which is considered as the single output, which is a substitution for thrust that is practically not measureable when the engine is built into an aircraft [11].

2. REDESIGNED FUEL METERING SYSTEM FOR TS-21 BASED GAS TURBINE TEST BENCHES

The original TS-21 is a turbostarter for medium-sized military engines like R-29 of MiG-23 fighter aircraft that can be easily converted into turbojet and therefore it is frequently used as research equipment at different universities [12–14]. These engines have a standard fuel pump and control assembly, which allows the manual override of the original pneumatically operated bypass valve letting the engine operating conditions to be altered according to the demands of the research. This system, however, has several drawbacks, as it uses compressor discharge as the source of control pressure, which significantly changes throughout the operating range of the engine. That means, if one wants to set an intermediate rotating speed, thus a calculated control pressure is obtained through a proportional valve, the former will change during the transient as the source conditions vary, even if the control voltage is maintained at the required level. This introduces difficulties in the control, which may be inaccurate, or even it may not be stable. Another disadvantage is that the needle valve is located in the bypass lines, so its opening reduces the output to the combustion chamber, resulting in a reverse logic of the control.

For the above mentioned problems, the authors have decided to establish a novel fuel metering system based on conventionally used solutions from the aviation industry. In many FADEC systems there is a metering valve in the supply line and a parallel connected differential pressure valve that keeps a constant pressure drop across the metering valve by letting a given flow back to the inlet of the pump. The opening of the metering valve is controlled electrically by the control system; the opening of the differential pressure valve is always adjusting automatically by the pressure forces. With this build-up, the amount of fuel flow is proportional to the opening of the metering valve, which significantly simplifies the control law. The layout of the system can be seen in Fig. 1.

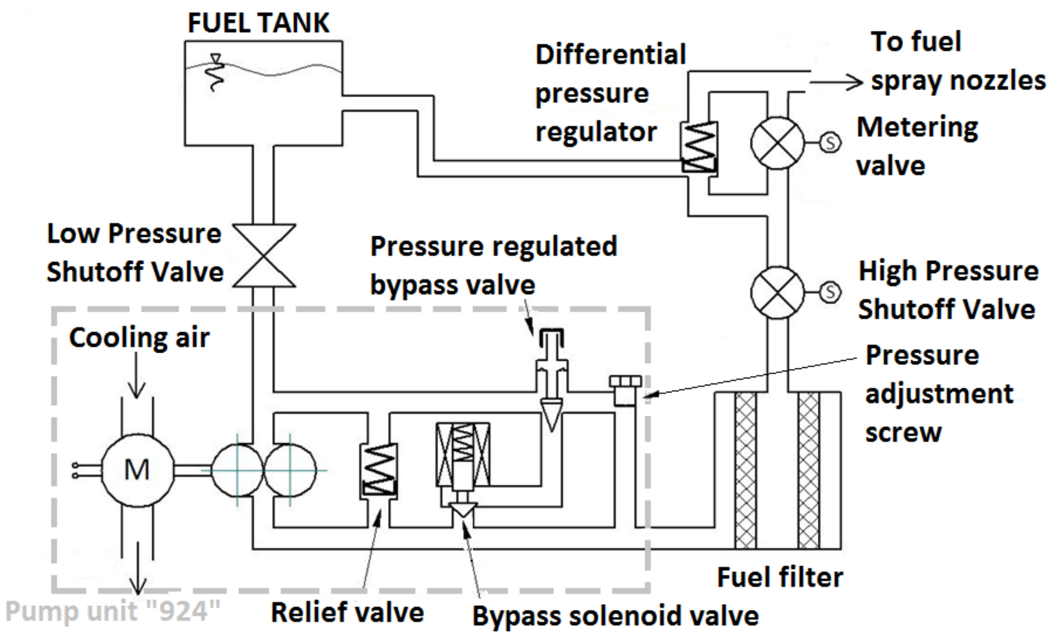

Figure 1 Fuel supply circuit for the gas turbine with proportional metering valve and differential pressure regulator connected downstream of pump unit 924 (based on [15])

The fuel consumption of the TS-21 is about 70kg/hour, which can be handled with an ASCO SCG202A051V type proportional valve [16]. This type offers an advanced control that is solved with an additional Series 908 electronic proportional control unit, which allows various inputs like industry-standard 4…20mA, or 0…10V signals [17].

As the pump unit “924” contains a positive displacement gear type pump with a fixed supply voltage, one can suppose a nearly constant speed drive, hence the volumetric flow at the pump outlet does not change significantly over a considerable range of operation. However, the consumption of the gas turbine ranges from nearly 30kg/hour up to 70kg/hour, so a wide range of usage must be adapted to the nearly stable supply. Even if the proportional metering valve is adjusted, if there would be no other means of bypass, the valve would be able to pass the complete amount of fuel from the metering valve.

One must state that there is a safety check valve in parallel with the pump that can relieve extreme downstream pressures if the orifice would create dangerously high pressure. However, it only opens in case of abnormal pressure; so it cannot be utilized solely, its characteristics would not be suitable for the control purposes. Let us consider the metering valve in a fully opened position first. In this case there is a small pressure drop across the valve, surely not enough to open the relief valve. Then we slowly close the metering valve, thus the pressure at the valve inlet is rising, once reaching the crack pressure of the relief valve. The valve spring yields and lets the valve to open in a very narrow range of pressure; therefore the majority of the fluid is able to return to the pump inlet, reducing the outflow suddenly. It is evident, that this way is not suitable for adjusting the fuel flow; one must use an additional unit, a differential pressure regulator.

The differential pressure regulator is connected in parallel with the metering valve, allowing a constant pressure drop across the MV in all operating conditions. This is possible as it has a third port directing unwanted fluid back to the inlet of the pump. The constant pressure drop creates a regulated flow velocity according to Bernoulli’s law across the metering valve; hence the volumetric flow will be simply proportional to the actual free cross-section of the metering valve.

The authors have selected a Duplomatic PCK06-PT three-way differential pressure regulator, that has a maximum bypass flow of 40dm^3/min. The valve is available in a cartridge so the housing had to be created according to the guidelines of the manufacturer [18]. According to Fig. 1, there is one major difference regarding system layout in contrast to conventional aircraft engines; namely the bypass outlet is guided back to the tank instead of directly upstream of the pump, because the former was simpler to solve. The newly introduced equipment can be seen in Fig. 2.

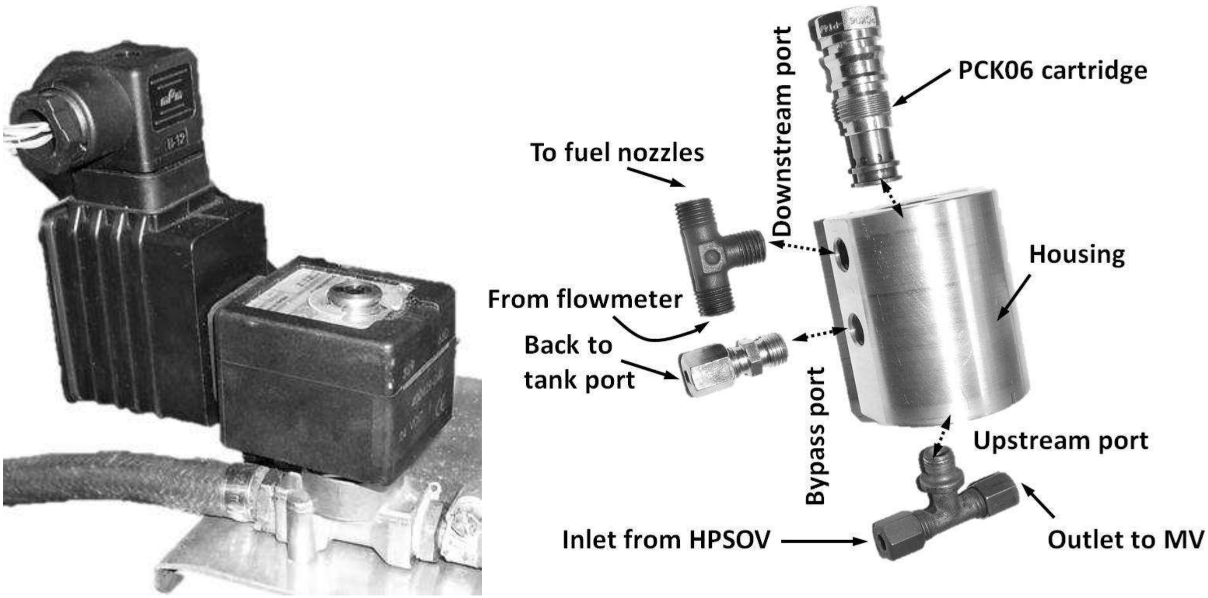

Figure 2 ASCO proportional metering valve (on the left) and Duplomatic PCK06 differential pressure regulator with its associated equipment (on the right, source [15].)

3. HARDWARE OF THE ELECTRONIC SYSTEM

3.1. Main microcontroller

The hardware of the experimental electronic system has been built around the *mbed* LPC1768 test board that allows the user to explore the most important features of this microcontroller. Although the integrated circuit has a total of 100 pins, the test board has only 40 connections including power supply, so the full capability is not completely exploited, but the majority of the functions can be implemented. The *mbed* system has a fair explanation of the different features [19], and there are several example projects available on the community website [20], both significantly reducing the complete time of development. The build-up of the test board with the possible connections to the environment can be seen in Fig. 3. Its 40-pin dual inline format allows simple installation into breadboards or fast prototype wire connections.

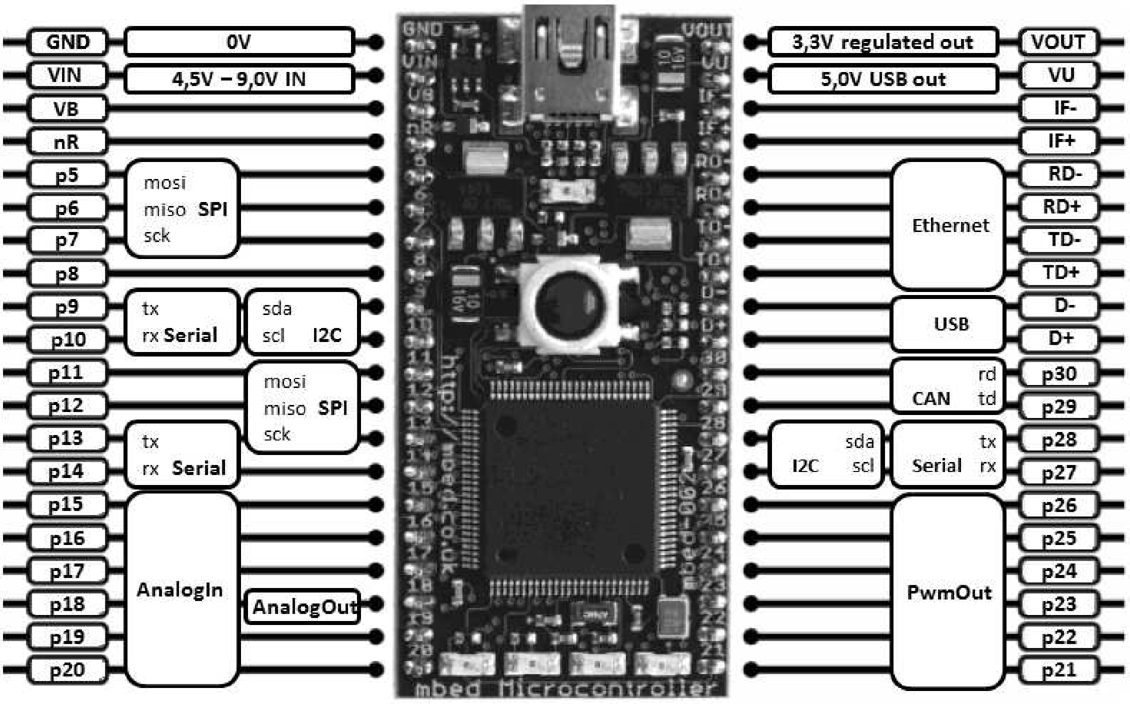

Figure 3 Peripheral connections of *mbed* LPC1768 test board

The technical data in the following paragraphs have been taken from the NXP LPC1768 data sheet [21].

The heart of the *mbed* test board is an NXP LPC1768 microcontroller with architecture of 32 bits and an ARM Cortex M3 core. The maximum clock frequency equals to 100MHz that enables fast computing of more complex tasks, e.g. floating point operations or similar. The memory consists of 512kB flash ROM for program code and there is a 32kB SRAM block for the processor.

The microcontroller has several hardware peripherals, including various analog and digital ones as well. The *mbed* board can use the chip's I^2C, SPI, Ethernet, UART, USB or CAN busses. This allows an easy interfacing with almost any computer system. The digital lines can also be used as discrete input or output lines to control or monitor two state devices, e.g. solenoid valves, or similar. In case of pulse width modulation, which is also widely used proportional control in the industry, the board offers six outputs. These are wired to a total of four independent timers, enabling different frequencies if necessary.

Typical applications can use analog inputs (e.g. throttle lever angle), on this board there are a total of six outputs are connected from the eight channels of the IC, they can be found on pins 15 to 20 of the prototyping board. The A/D conversion uses multiplexing technology (i.e. only one conversion is in progress at a time), has 12bits resolution and a maximum of 200kHz sampling frequency.

The present investigation necessitates the analog output to create sine wave excitation for the metering valve. The controller requires an input voltage in the range of 0…10V as stated above to drive the valve between fully closed and fully opened stops into a proportional position corresponding to the control input. However, the *mbed* gives only a maximum analog output that equals to its supply voltage, which is 3.3V. Therefore an amplifier is required, which is described later in this chapter. The resolution is 10bits, which is still fine enough; it allows steps of approximately 0.1% of the complete range.

3.2. Level shift and protection circuit

As it was stated above, the analog output is not able to generate signals that would completely fit into the range of metering valve controller input. Another problem is that the high voltage parts should be separated in order to protect the delicate microcontroller from accidental overstress.

The first function could be realized by a simple transistor, which is designed to amplify the voltage coming from the analog output to a suitable level. However, the lines in the circuits are in a galvanic contact with each other, i.e. in an abnormal situation the microcontroller could receive dangerously high voltages originated from the supply of the valve itself. Therefore the authors have chosen an optocoupler solution that incorporates a light sensitive transistor and a light emitting diode in a common package. The component selected for this purpose was the ILQ74, which includes a total of four independent channels, which provides the possibility for further development as well. Thus the microcontroller analog output is sending current to the LED, which is in turn sensed by the phototransistor and converted into a proportional current on the secondary side. This layout ensures full separation between low and higher voltage supply circuits.

However, each solution can have drawbacks, this method increases the dead zone of the output, namely the LED inside the optocoupler package needs a minimum voltage to conduct. Below this voltage level there is no current transfer possible, the output side does not receive any signal. Typical forward voltage of the selected device is approx. 1.3V [22], i.e. the useful range up to the 3.3V supply voltage reduces to 2V, in another viewpoint the analog output should increase to approx. 30% to begin the operation.

On the other hand, the optocoupler includes an NPN type phototransistor, which is then included in the circuit as a low-side switch, and it needs more excitation to reduce the output voltage. Finally, one can state that the analog output and the voltage sent to the valve are reversed in phase, which will be important later, when control for the gas turbine engine is to be developed.

Due to the experimental setup, this electrical circuit has been realized on a breadboard. Its logical schematic can be found in Fig. 4.

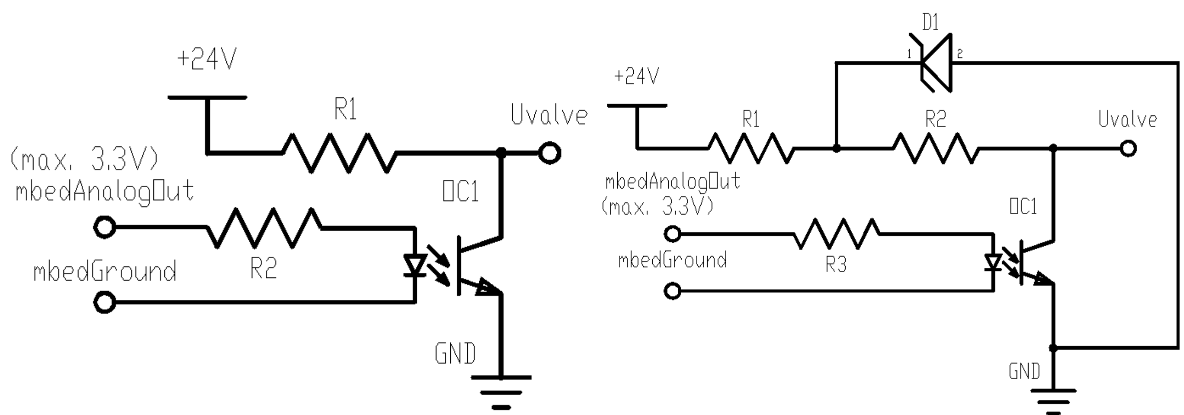

Figure 4 Theoretical schematic of supplementary circuit a) original; b) with additional Zener diode

The resistors have been selected to provide a suitable transfer function of the circuit. R1 is the current limiter for the Zener diode, its value is 1kohms. R2 is a 3k1 resistor which allows the collector of the optocoupler to have different voltage level in contrast to the Zener diode. Finally, R3 is the current limiter for the LED, in order to increase current output within the allowed range of the optocoupler. It has been selected to 67ohms, the corresponding current is nearly 30mA supposing supply voltage of 3.3V and 1.3V typical forward voltage of the LED, the ultimate limit for the package is 60mA according to [22].

However, there was another issue to solve. Even if the control voltage of the valve should fall within the range of 0…10V, the *mbed* is running on 3.3V, the valve coil itself accepts a 24VDC supply. The simplest solution is to limit the voltage sent to the valve controller at a maximum of 10V with the usage of Zener diodes; the type ZPY10 has been selected for the current application as it has the same nominal voltage that is required. According to Fig. 5, without Zener diode, the maximum allowed voltage would be reached at an analog output of 60%, while the control voltage would saturate at 80% of the analog output, resulting in a useable range of only 20%. Even if the Zener diodes were not enough to broaden the range to an optimum, the useful range reaches almost double of the original with a lower value of 30% and saturation at nearly 70% of the maximum analog output [15]. As the primary goal was to establish a system that is able to operate correctly, the optimization has been selected as a further possible development.

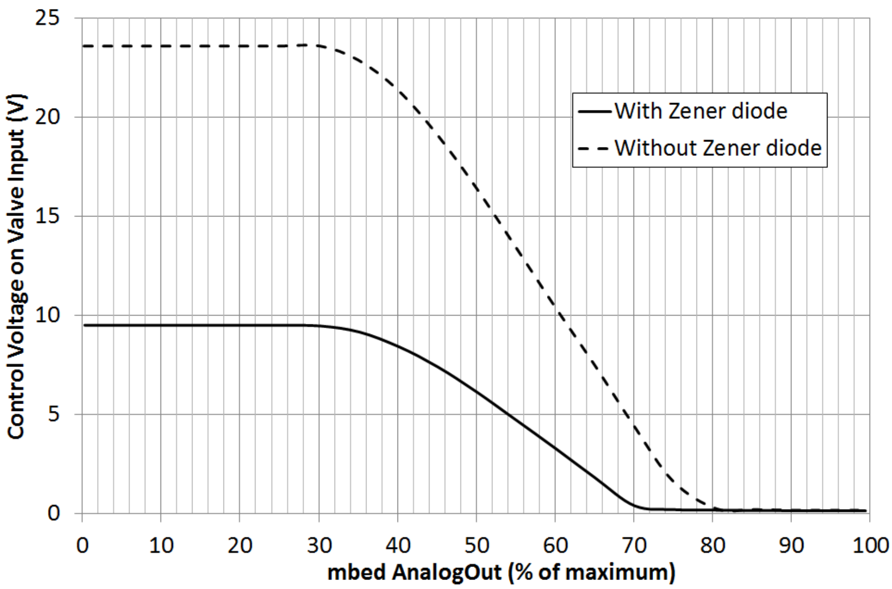

Figure 5 Correlation between *mbed* AnalogOut (percentage) and control voltage of the metering valve (based on [15])

4. SOFTWARE FOR IDENTIFICATION OF SYSTEM’S TRANSFER FUNCTION

The main program contains basically the preparation for the majority of the tasks only and the real operation is performed by interrupts. As the system will operate later as controller a main cycle has been determined using the Ticker object of the *mbed*. This has been set to run 50 times each second, i.e. with 20ms timing. The LPC1768 uses two analog inputs to determine the opening of the metering valve and the amplitude of generated oscillations. The conversion of these analog inputs is performed in the main cycle at this time along with sending data to the analog output. Later this subroutine will contain the control law as well.

Another Ticker object is defined as minor cycle; such less important functions like displaying data on an LCD will run every 0.5 seconds. Thus the refreshment of the real-time data and slow outputs do not interfere with each other.

Sine wave generation is similarly solved with Ticker, but its period is changing as it proceeds and it is not running all the time. It can be initiated by pressing a button, which needs an additional DigitalIn component. After the command has been sent – it is to be performed by the user when the required mean fuel input level and the amplitude of the oscillations have been done – the Ticker is activated with a frequency corresponding 1/360 of 10 seconds. At each cycle it computes the sine of the actual cycle counter which realizes then steps of 1 degree. At this point there is a connection to the analog output, where the actual value must be refreshed. If the counter reaches the complete 360 steps, it detaches the Ticker object, i.e. it temporarily suspends operation, but immediately – in the same subroutine – the period is reduced in order to perform the same process with an increased frequency. Then the Ticker is restarted with the new period. This repeats until period reaches 0.1 seconds. Finally, the Ticker is suspended until next command. In order to reduce the total time consumed by this process, the periods longer than 1 second are not repeated, while the shorter ones have an increasing count for repeat. This ensures the measurement for short periods can be performed with the desired accuracy.

As the system is based on the *mbed* prototype board, the online compiler has been used for the development of the software.

5. RESULTS, CONCLUSION

The authors have conducted more measurements in order to verify the correct operation of the system before attempting to activate its main features. As the results of these experiments were satisfactory, a real measurement has been performed on the turbojet engine.

The engine has run at a steady operating point selected by the throttle potentiometer input, then, by activating the special mode, the oscillations have been generated automatically by the *mbed* system. The complete operation is indicated in Fig. 6.

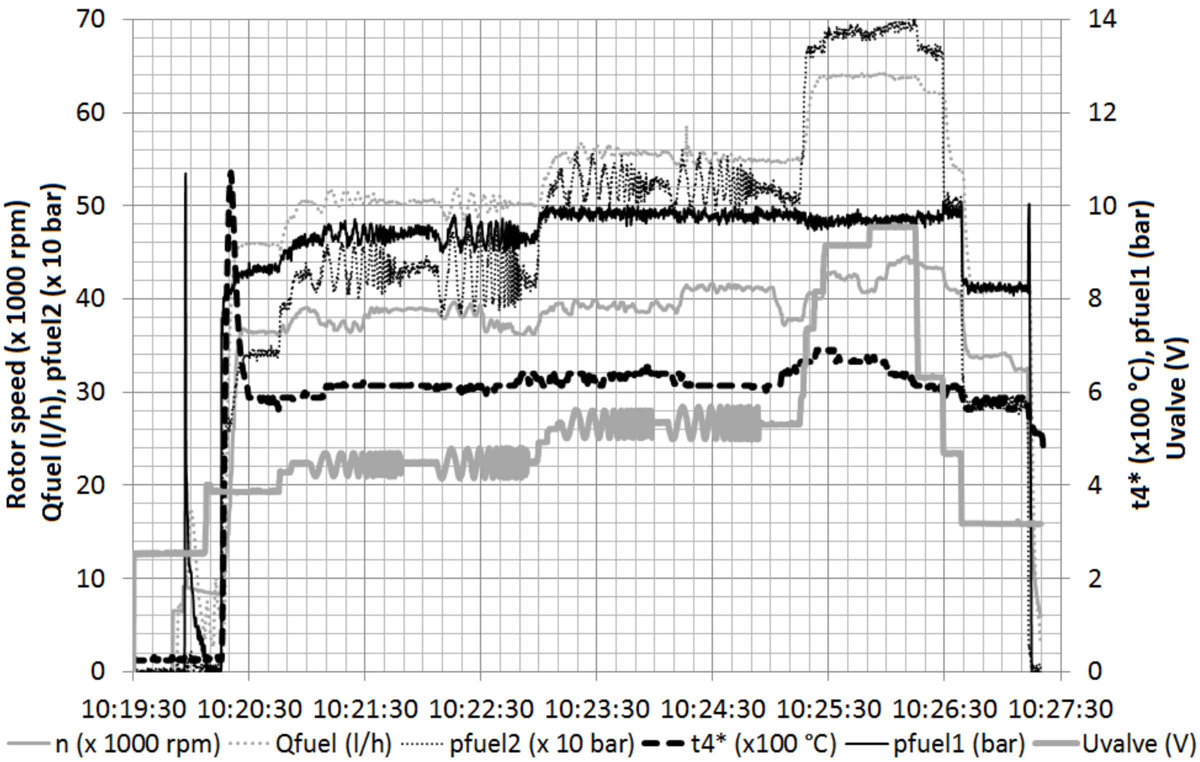

Figure 6 Test run of turbojet engine including four special modes for identification

Based on the results indicated in Fig. 6, one can state that the developed embedded system is fully capable of those features that have been selected. The engine operation is responding correctly to the analog output of the electronics, which will be the basis of a more complex control system. We have to underline that the present state of the development has the only possibility for manual (open loop) control; the throttle potentiometer signal is simply converted into a proportional value on the analog output. The additional feature which has an importance in the identification is the special mode creating the sine wave oscillations. Figure 7 shows the details around a selected transient mode to allow evaluation of these parameters. It can be seen, when the control voltage of the metering valve begins to swing, there is a slight delay in the system, i.e. pressures and flow does not immediately react. The only smooth curve is the control voltage, as it falls between 4 and 5 volts (during the present part of the operation), the other signals are measured as smaller 4…20mA signals, therefore they carry significant noise, which should be improved in the future. The small arrows below the parameters determine on which scale their values can be seen.

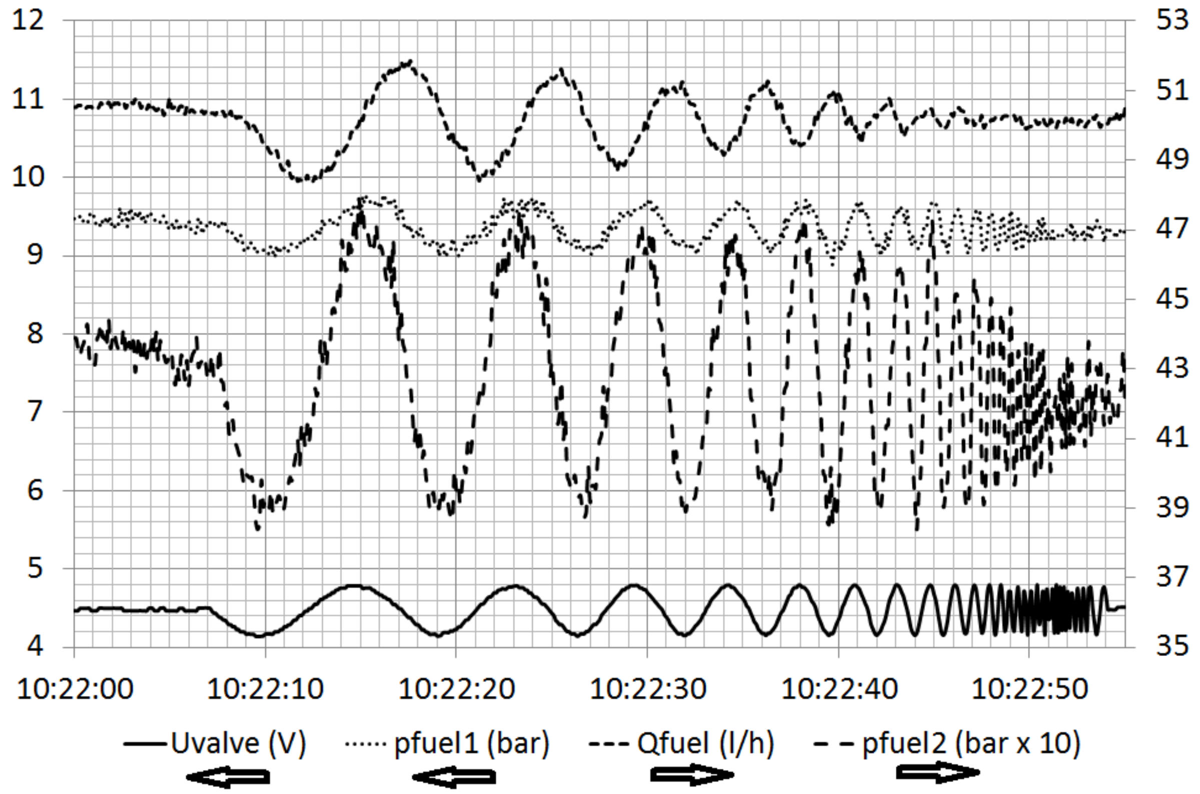

Figure 7 Details of a single special mode showing increasing frequency sine wave excitation

After performing such a measurement, one has to select a variable, which will be used as a controlled parameter. In turbojet systems, in many cases this is the rotor speed, or others like engine pressure ratio or Turbofan Power Ratio can be utilized as well. With the help of advanced computational software like MATLAB one can perform the identification, after the input and output has been determined, the program can compute the relationship between the two signals, which will yield the transfer function of the system. Due to the complexity of this process, we do not describe the details here; it will be presented in a different article later during the research, together with the design of the control.

As conclusion we have to mention that our primary goal to develop a device which can help to create sine wave excitation for a gas turbine engine during identification process has been reached. The unit is able to perform the desired task with sufficient accuracy in resolution of output voltage levels as well as it has fast response in time.

As gas turbine units incorporate significant nonlinearities, the identification should be repeated at various operational conditions from idle to maximum power. This can be quite easily done with the help of this unit as it gives the possibility to manually select operating circumstances by adjusting the fuel input through the throttle potentiometer then starting the special mode after the engine has stabilized at the desired condition. This way the complete operating envelope can be measured with a few repetitions.

Despite the termination of the first step of development, it still has several ways to continue. First of all it must be stated that the final aim is to design a control system for the gas turbine engine based on the data that have been acquired using this equipment. For this reason the functionality of the electronic device must be extended, depending on the parameter that will be selected either a frequency counter (for rotor speed) or analog input (for pressure) should be added to the current layout. The software must be significantly improved to include those routines that handle the control law, e.g. discrete time PID algorithm or even more complex solution, but those will require a different method for identification as well.

The functionality of the identification could be improved, too. For example, a previously determined program could be also included, which defines those operating points that should be involved in the measurement. Thus, instead of manual setting of different regimes, the automatic system could perform the transients quicker and more accurately than human interaction, thus optimizing consumed service life of gas turbine and used amount of fuel, which both can be important in any applications from low-budget university projects up to industrial environment.

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