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DEVELOPMENT OF IMPROVED DATA ACQUISITION SYSTEM FOR A TURBOPROP ENGINE TEST BENCH

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Summary. Turboprop engines are commonly used in medium-sized short-haul airliners, where they have a significant fuel efficiency benefit over conventional turbofan engines. These units have therefore a constant interest in aviation development. The goal of the presented paper is to describe the development of an enhanced data acquisition system that has replaced an old one, which had significantly restricted capabilities. The newly designed system is intended to be used in both education and research; consequently it must present several state-of-the-art features. Therefore the system has been based on a National Instruments USB multifunctional data acquisition device, which does not simply allow the measurement of the parameters but provides the interface for controlling the engine as well. In order to improve visual interpretation of the measured signals, the software has been elaborated in NI LabVIEW environment. For enhanced interaction of the user, the old up-down control of the throttle lever has been extended with a proportional control as well. The authors have conducted sample measurements using the new system to verify correct operation.

Keywords: gas turbine engine; turboprop engine; data acquisition system; gas turbine test bench; LabVIEW

1. INTRODUCTION

The aim of this article is to present a newly developed data acquisition system that replaces a former version with strongly restricted possibilities. The intent of the authors was to design and build such a system which can satisfy the various and often different demands of both educational and research purposes.

Although medium-to-long-haul aviation almost exclusively relies on high and ultrahigh bypass ratio turbofans [1], the aircraft used in regional air transport are still driven by propeller; mostly by turboprop configurations due to the favorable power-to-weight ratio of gas turbine engines and the superior propulsive efficiency of propeller in the moderate subsonic velocity range [2]. Due to their relatively wide usage it is important to conduct various researches in order to improve these power plants, as well as to incorporate them into the education of aeronautical engineers [3].

Turboprop engines have different major mechanical configurations. In the past, the first types featured a single shaft, on which an oversized turbine was responsible to drive its own compressor and, furthermore, the propeller through a reduction gearbox [4]. This structure did not give enough flexibility, as the efficiency had to be improved, it necessitated larger compressor pressure ratio. This, in turn, has led to divide the rotating assembly in more than one shaft, separating the propeller drive system from the power section, which, sometimes, is also called as gas generator, regarding the primary function to develop high energy gasses to drive the free power turbine and produce shaft power to move the propeller finally [5]. This latter, the multi-shaft configuration is spread more widely nowadays. Depending on the complexity of the compressor, the power section itself can be of a two-shaft configuration; in this situation, the complete engine has three shafts. Despite the constantly growing complexity, the improvement of the fuel efficiency necessitates these design considerations.

At the Department of Aeronautics, Naval Architecture and Railway Vehicles of BUTE there is a gas turbine test bench using a Klöckner-Humboldt-Deutz T216 type turbine engine developed for producing shaft power. It is of a single-shaft configuration, which is not considered up-to-date nowadays; however, the possibility of investigation of thermodynamic cycle and conduct research like enhanced control systems makes it a valuable device, as there is a constant demand on micro gas turbine power plant research [6-8], also in such emerging fields like renewable fuels [9].

2. DESCRIPTION OF THE DEUTZ T216 TEST BENCH AND ORIGINAL DAQ SYSTEM

2.1. KHD T216 gas turbine engine

The Klöckner-Humboldt-Deutz T216 is a multifunctional turbine engine developed for various fields of the industry: to provide emergency electrical supply for safety-critical applications like hospitals, drive pumps for fire fighting vehicles, etc. For this reason, considering the basic operating conditions on ground, it was not a primary goal to achieve excellent power-to-weight ratio, in contrast to aircraft propulsion systems. This also necessitates a minimized maintenance requirement as such operators would not be able to correspond to strict technical orders commonly used in aviation. On the other hand, it has been developed to accept different fuels not limited to aviation kerosene but including Diesel fuels. Its design features high mobility as well, adding a further benefit to the above mentioned ones [10].

All of the above mentioned properties of the engine make it especially suitable for university installation in order to involve it in both education and research as it has been reported in [11;12].

The sectional drawing of the single-shaft gas turbine can be seen in Fig. 1. It features a centrifugal compressor with a pressure ratio of 2.8:1 at nominal operating conditions, which is 50000rpm shaft rotational speed. There is a single combustion chamber of a tubular configuration. The radial turbine drives the compressor and the reduction gearbox, on which the engine accessories as well as the main output shaft. The system includes a flyweight governor that keeps a constant rotor speed determined by the throttle lever. There is an autonomous starting and ignition system including a three-phase AC starter motor and a spark generator delivering high voltage pulses to the single igniter plug. Lubrication to the bearings and gears in the gas turbine as well as in the reduction gearbox is provided by a pump unit driven through the gearbox itself [13].

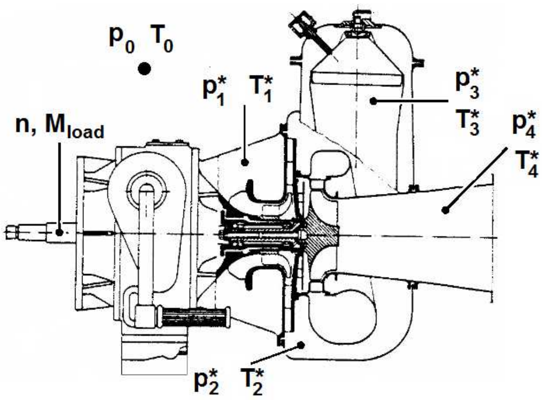

Figure 1 Longitudinal section of Klöckner-Humboldt-Deutz T216 turbine engine (based on [10])

2.2. Original data acquisition system

The original data acquisition equipment was already phased out at the time of creation. It was built around a personal computer featuring a 386 processor. The analog-to-digital conversion has been accomplished by an Advantech PCL-818 card. Although the hardware had already several limitations due to its obsolescence, the largest problem originated from the software.

The original DAQ software allowed basically static measurements consisting of ten seconds stabilized operation at a selected regime. There was a strongly limited possibility of transient process measurement; it allowed recording of a 5.5s period with a sampling rate of 18.2Hz. This reduced capability was not enough to carry out detailed investigations. Furthermore, the program did not save the measured data automatically; hence there was a high rate of data loss [13].

2.3. Measured parameters

The original configuration already allowed the measurement of several parameters, which are related to the operation of the gas turbine engine.

Five pressures and temperatures were monitored at cross-sections depicted in Fig. 1. These are the ambient (station 0), compressor inlet (station 1), compressor discharge (station 2), turbine inlet (station 3) and turbine exhaust (station 4). It is also very important to measure rotor speed n and the load torque M_{load}. In the evaluation of a gas turbine the fuel consumption is of high priority, which is provided using a collector tank. The collector tank has a solenoid valve to the main tank, which feeds fuel to the collector tank by gravity if the solenoid is controlled open. If the solenoid is closed, the gas turbine consumes the fuel from the collector tank, whose weight can be measured with a strain gauge.

Air mass flow rate is another important figure of gas turbine operation. In industrial applications – both aviation and land-based ones – this parameter is normally not measured, but for deeper investigations it is beneficial to monitor. Therefore an inlet orifice has been applied to the air intake duct that creates a pressure drop proportional to the flow; this pressure differential, called as Δp_m can be measured by a further pressure sensor.

In the original configuration the position of the throttle lever was only monitored by three limit switches: the minimum position one is responsible for stopping the gas turbine operation by biasing the governor to cease fuel supply; the second microswitch determines the idle position and the last one is dedicated to maximum rotor speed condition.

3. DEVELOPMENT OF NEW DATA ACQUISITION SYSTEM

3.1. General concepts

All the above mentioned restrictions of the former system have led to the need of complete redesign of the data acquisition.

The goals were to improve system functionality, in terms of sample rate, user-friendly solutions like automatic saving of the measured data, better visualization of the information for real-time interpretation of the data.

As the authors have several years' knowledge in LabVIEW programming environment as well as various National Instruments data acquisition devices, the choice was made for this software supplemented by an NI USB-6218 multifunctional unit.

3.2. New hardware for data acquisition

The NI USB-6218 multifunctional device has several advantages, which were taken into account during selection phase. It does not simply include 32 individual analog inputs but also features two digital-to-analog converter channels, eight digital inputs and eight digital outputs as well. Some of the digital inputs can be configured as counter inputs, which is very useful in rotor speed measurement. The digital outputs can be used for controlling two-state devices around the test bench, e.g. fuel solenoid valves, starter motor, etc. [14]

Due to the USB connection and advanced driver for NI LabVIEW it is quite easy to set up a measurement with the device. However there are several unused inputs currently; the impending improvements will surely require the possibility for extension, which is already present.

The device allows an aggregate maximum sample rate of 250 thousand samples per second, i.e. with approximately twenty channels in use the overall sampling can reach up to 10 thousand complete cycles per second. This means a nearly 500 times faster data acquisition in contrast to the initial system that allows the deeper insight into quicker transient processes as well.

The resolution of the unit is 16 bits, compared to the PCL-818, which featured a 12-bit analog-to-digital converter. This significantly improves the accuracy as well: differential nonlinearity is 0 least significant bits; integral nonlinearity is 76ppm regarding the full scale, i.e. in a maximal ±10V range it only means an error of 1.5mV. Taking into account some other important sources of error like conversion noise, gain error, zero offset error, the maximal absolute error of the measurement lies around 2.7mV, which is reasonably small [15].

It is important to illustrate the layout of the channels that are currently in use. This can be seen in Table 1.

Table 1 Channel layout of NI USB-6218

Pin number	Factory designation	Signal description
1	PFI0 / P0.0	Throttle at idle
2	PFI1 / P0.1	Rotor speed
3	PFI2 / P0.2	Throttle cutoff position
4	PFI3 / P0.3	Throttle full power position
6	PFI4 / P1.0	Throttle up digital
7	PFI5 / P1.1	Throttle down digital
8	PFI6 / P1.2	Collector tank solenoid
9	PFI7 / P1.3	Starter motor
12	AO0	Throttle down analog
13	AO1	Throttle up analog
24	AI4	T_1^*
25	AI12	T_2^*
26	AI5	T_3^*
27	AI13	T_4^*

Pin number	Factory designation	Signal description
33	PFI8 / P0.4	Throttle at idle
40	PFI14 / P1.6	High pressure shutoff solenoid
41	PFI15 / P1.7	Low pressure shutoff solenoid
47	AI16	Throttle position (analog)
49	AI17	p_0
50	AI25	Δp_2
51	AI18	Δp_3
52	AI26	Δp_{mp}
53	AI19	Δp_1
54	AI27	Δp_4
56	AI20	T_0
63	AI23	Collector tank load cell
64	AI31	Output torque

3.3. Operating software in LabVIEW environment

Due to several successful applications in the same field the software NI LabVIEW has been chosen to realize the operating program for the data acquisition system. This environment basically differs from traditional programming languages as it features a graphical programming interface rather than a conventional text-editor interface. This alone can ease up the process of software design; furthermore, the support for device drivers can offer an additional significant advantage.

The program in LabVIEW environment is composed of two major parts: the Front Panel and the Block Diagram. The former acts as human-machine interface; here different types of controls and indicators can be placed according to the demands of interaction with the user. The latter replaces the traditional text editor source code; it contains nodes that are connected with wires to carry the information among them [16].

In the presented work the software's main goal can be summarized as follows:

- collects data from DAQ hardware;
- accomplishes transformations from raw data to physical properties;
- indicates the results of conversion on the Front Panel in real-time;
- saves the data immediately to mass storage of the host computer.

These steps are provided mostly by built-in functions or factory-supplied device drivers. The data storage is emphasized in contrast to the original version, which is automatically scheduled in every main cycle in order to ensure minimum chance of data loss. Data are saved in a plain tabulator-separated text file, which can easily be read and processed by spreadsheet software.

In Fig. 2, one can see the layout of the Front Panel's main view, labelled as "Turbine". It shows a schematic sectional drawing of the gas turbine on the right side, which surrounded with the thermodynamic parameters from each main aerodynamic station. The main fuel supply components, including the collector tank, which contributes to the fuel consumption measurement, are also depicted near the right top corner. In the centre of the figure the main control pushbuttons can be seen: these are dedicated to operate the following:

- starter motor, which drives the ignition as well;
- high pressure shutoff valve for fuel supply to the combustion chamber;
- low pressure shutoff valve that enables fuel flow to the fuel pump;
- collector tank inlet solenoid, which is automatically controlled by the software to facilitate the measurement of fuel consumption.

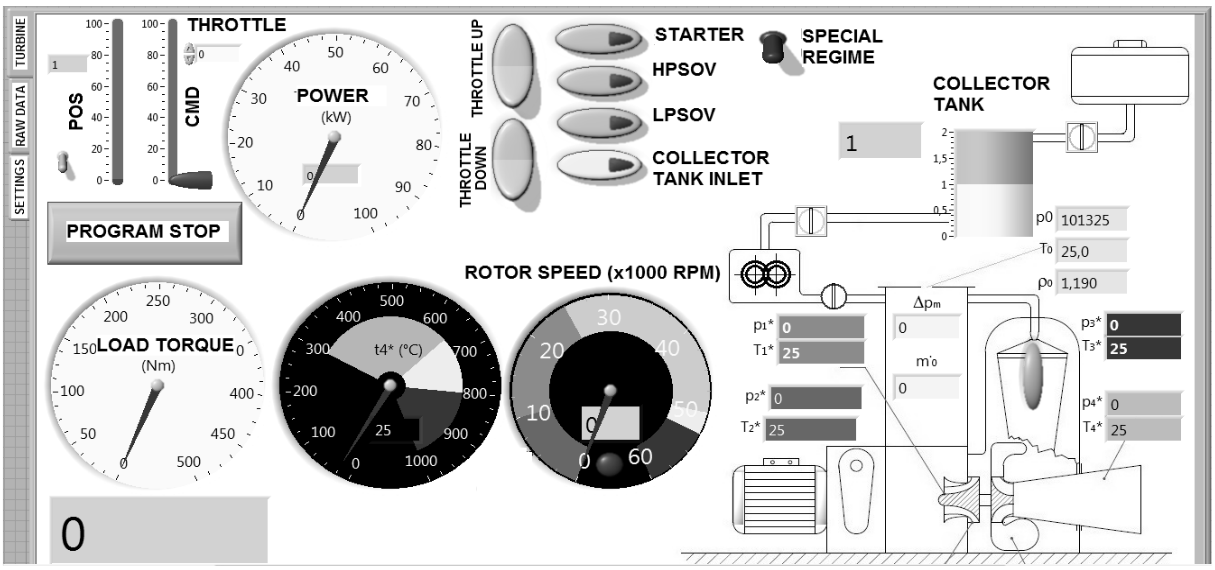

Figure 2 Front Panel of LabVIEW software

There are also the main symbolic gauges found on the left side in Fig. 2. These are the rotor speed and exhaust gas temperature, load torque and power.

For throttle control, the program provides two different ways of movement. The original solution consisted of two relays, which were able to connect the DC power to the throttle positioning motor in the straightforward and reverse order resulting in "throttle up" or "throttle down" movement, respectively, until the user keeps the control buttons pressed. This simulates the original hardware configuration that realized the same operation with physical pushbuttons.

There is an important improvement that is also detailed in the next subchapter. The related control and indication can be found in the left top corner of Fig. 2, where a linear indicator labelled "POS" and a linear control called "CMD" can be seen. This incorporates an automatic control, which is realized by the software of the block diagram and has the role to maintain the throttle position selected by the user. See details in subchapter 3.4.

The operating program incorporates several other functions, which are not visible all the time. These features can be accessed if the user selects the tabs on the left: either Settings or Raw data. The former allows the user to adjust coefficients and physical channels for different inputs, and other main parameters for the data acquisition. The latter enables the inspection of raw inputs of all channels in order to allow for debugging and calibration.

3.4. Automatic control for the throttle positioning motor

Probably the most important improvement of the system is the extension of the throttle positioning system. The original configuration, as it has been stated above, was built on an “up-down” control by manual operation of the throttle positioning motor until the required rotor speed has been reached.

The new concept was to improve the throttle positioning with an automatic control that allows the user to select a throttle position (rotor speed) according to the needs, and the system will control the motor until the required position is reached. The implementation of this change required several steps detailed below.

First of all, the throttle position has originally been monitored by only three limit switches regarding different notable positions as cutoff, idle and maximum power. For a proportional control one needs the feedback from the entire range of travel. Therefore a potentiometer has been installed in the vicinity of the throttle lever that is driven by the electric motor. A pushrod provides the mechanical connection between the two; the potentiometer has been connected to A/D channel No. 16 of the NI USB-6218 DAQ unit.

All automatic control concepts (e.g. PID, which has been selected by the authors) generate a drive signal that is proportional to the error between actual and reference values. If the user moves the control on the screen to the required throttle position the software will operate the motor in the required direction with a speed proportional to the extent of the deviation of the actual from the reference. That means, not only the direction of the operating voltage but its magnitude shall be controlled as well. For this reason, an H-bridge has been designed [17]; the layout of the circuit can be seen in Fig. 3.

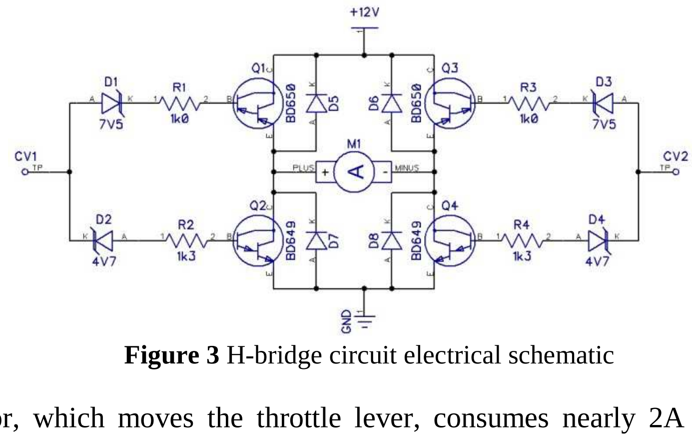

Figure 3 H-bridge circuit electrical schematic

The electric motor, which moves the throttle lever, consumes nearly 2A current from 12VDC power supply. This is the extreme condition which has been considered during the design of the H-bridge circuit. For this reason, Darlington transistors of type BD649 (NPN) and BD650 (PNP) have been selected. These feature an 8A maximum current rating at an ultimate 100V collector-emitter voltage. At the design stage already it has been noted that the NI USB-6218 has only two analog outputs that can be used as control signal for the transistors. Therefore the H-bridge must contain Zener diodes to allow for common control of transistors on the same side, which are working opposite of each other.

The Zener diodes labelled as D1 through D4 have been selected to allow for a neutral zone of the control voltage around half of the supply voltage. This is required to ensure both transistors of the same side are controlled off safely, within the dead band of approximately ±2V no operation is supposed. If the control voltage falls below the lower threshold, the upper PNP transistor opens; in the opposite case the NPN transistor will conduct. It must be noted that this circuit is working in a proportional manner and not only in switching-mode, i.e. a small deviation from the threshold voltage will result in a reduced current supply causing a slow motion of the motor. If quicker movement is required, the transistors can be opened more. The system allows a maximum speed of throttle lever motor that would drive the lever through the full range within 3 seconds.

The diodes D5 through D8 are protection diodes that allow the motor current to decrease if the transistors are suddenly controlled off. One can suppose the motor acts as a large inductance that would result in a voltage surge without protection diodes.

The initial state of the circuit is such that both control voltages CV1 and CV2 have a common 6V level, which corresponds the middle of the dead band, none of the four transistors is opened, no current flows in any direction through the motor M1.

In normal operation, the complementary devices of the opposite sides are controlled together, i.e. the control voltage CV1 is in a reverse correlation with CV2 to act on the required transistors. In case of throttle lever up motion, Q1 and Q4 are controlled; in the reverse direction Q2 and Q3 shall operate.

During the design of software control it has been taken into account that the controller will practically have an effect on the speed of the motor, meanwhile the feedback monitors the position, i.e. it already incorporates an integrator and helps to eliminate static error. Therefore a simple proportional control has been designed to the speed of the throttle positioning motor. As preliminary measurements have confirmed, the motor speed is negligible below 3V power supply, the range between 3V and 10V has been selected, also taking into account an approximately 1V saturation voltage of the transistors. A reasonably small static error of 1% of travel range is considered, outside of this region the motor control voltage increases proportionally with the error. The control voltage of the system is depicted in Fig. 4.

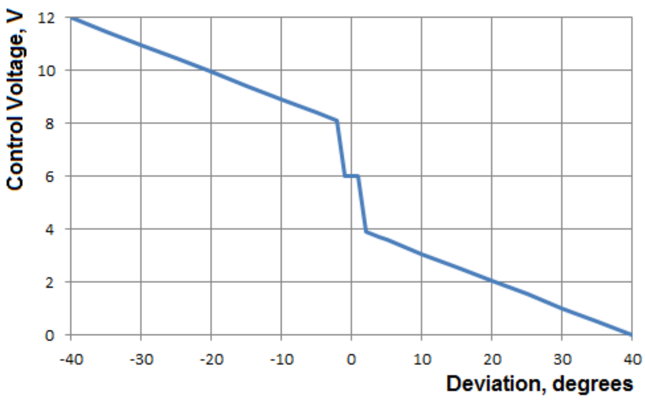

Figure 4 Transfer function of control system

4. MEASUREMENTS FOR VALIDATION

Several measurements have been conducted in order to verify correct operation of the system.

Firstly, the authors have calibrated the sensors with given physical references of the respective type, i.e. pressure, temperature, etc.

As the static test of the sensors has been finished, a reduced system test was performed using the starter motor. During the dry crank inspections the vast majority of the probes have been thoroughly verified.

The automatic throttle position control required additional testing in hardware and functionality as well. Finally, a complete engine run has been performed in order to validate the cooperation of system components altogether.

In Fig. 5 one can see how the various engine parameters are changing during a test run. Several rotor speeds and different output power values have been provided to illustrate the deviations in specific parameters. Rotor speed is the solid line in Fig. 5, output power is represented by narrow dashed line; temperature of compressor discharge (t_2^*) is shown as wide dashed line, turbine inlet temperature (t_3^*) is a dash-dot line, finally, turbine discharge temperature (t_4^*) is indicated by dotted line.

From the beginning of the measurement, the starting of the gas turbine engine can be seen. Turbine discharge temperature reaches a peak approx. 1100°C, significantly above the turbine inlet temperature. This is a strange situation as normally the latter should always exceed the former one, but one should mention that these data have been taken during the starting, in which the combustion process can continue throughout the turbine as the overall air mass flow rate across the engine is very small. During the normal operating range the normal relationship between the two temperatures can be found. It must be also noted that there is a single thermocouple that measures each temperature, i.e. they can be accidentally placed in adverse points of non-uniform temperature distribution.

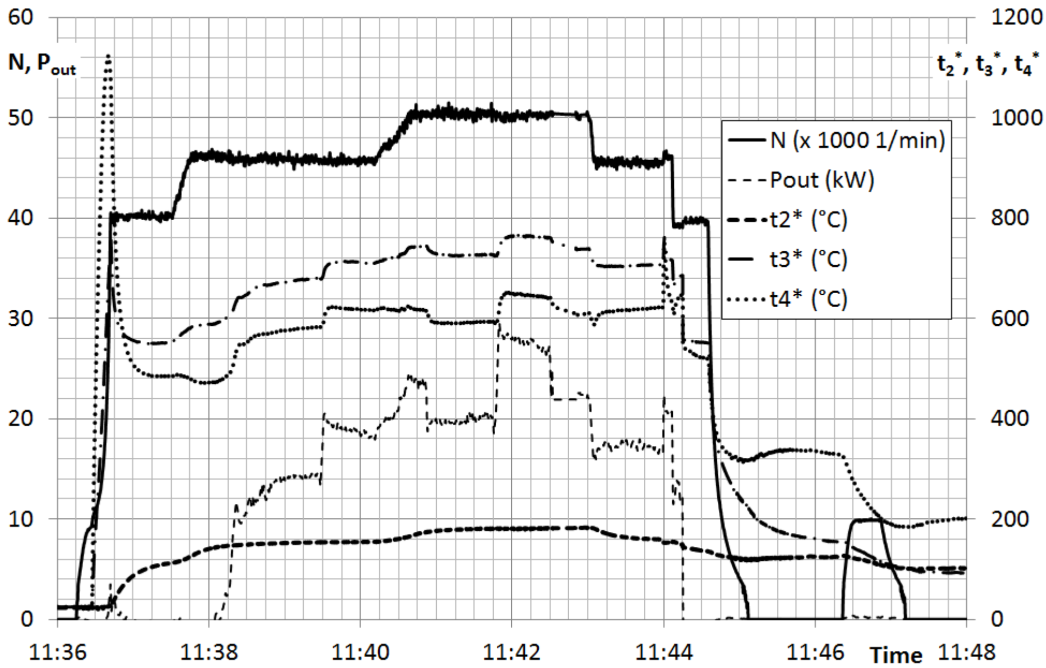

Figure 5 Engine test run temperature and power data

In Fig. 5 there are several steps in rotor speed, they represent the different operating conditions. Immediately after starting the engine, it was running in an idle condition at 40000 rpm, until the gas temperatures have stabilized at their respective values. From this point acceleration to 45000rpm has been conducted, which had a longer time for data acquisition, as the hydraulic brake unit was started (filled with liquid) at this time, and net output power has increased from zero to 15kW. Braking torque has been adjusted several times in order to change the output power of the unit, which can be evaluated in Fig. 5. Afterwards, the nominal speed of 50000rpm has been tested as well. After completing these dedicated operating regimes, the engine has been run at 45000rpm and finally an idle speed of 40000rpm has reached where the hydraulic brake was evacuated thus the braking torque dropped to zero and gas temperatures were able to stabilize at moderate values. After shutting down the engine a significant cooling period was performed using the starter in a dry cranking mode.

In Fig. 6 one can evaluate the engine test run based on different pressure related ratios. This diagram shows the rotor speed as well, it has been transformed to a normalized range relative to the nominal 50000rpm in order to fit into the ranges used by the other variables. Thus one can compare the results with Fig. 5.

As a logical order of measurement points, first is air mass flow rate $\dot{m}$ that is derived from differential pressure measured at the inlet orifice. It shows a strong proportional correlation with rotor speed, as the dash-dot line of Fig. 6 indicates. Second variable is compressor total pressure ratio π_C^*

which proportional to the square of rotor speed. This one is shown with dotted line. Another important factor of the gas turbine engine is combustion chamber pressure recovery factor σ_{CC}, represented by a dashed line in Fig. 6. It shows a minor change during the initial cold phase of starting, and reduces drastically as the combustion process takes place. During running conditions, it depends slightly on various factors, however, it can be seen that an assumption of constant σ_{CC} would not hold. The last indicated parameter is represented by a dashed line in Fig. 6, that is engine pressure ratio (EPR) that equals to the ratio of turbine discharge and compressor inlet pressures. It does not show a significant change until the hydraulic brake is applied, in other words, it reflects the net output power, as it can be compared to power curve in Fig. 5. Therefore EPR could be used as a parameter describing the actual power setting of the engine similarly to various turbojet and turbofan engines that use EPR for controlling thrust.

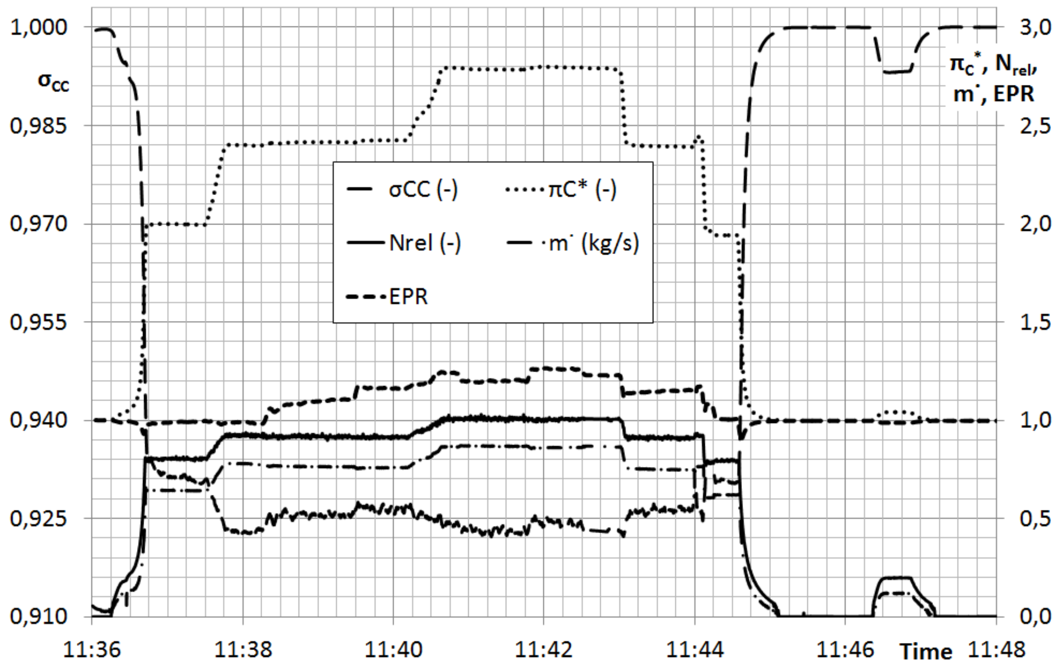

Figure 6 Engine test run pressure data

4. CONCLUSION

In this article the development of a turboprop engine test bench has been detailed. It is not only featuring a brand new data acquisition system with significantly extended capabilities, but also includes such modifications that allow for easier preparation and realization of various test schedules of both industrial and educational approaches.

The most important new functions include automatic save of the measured data minimizing the chance of data loss, enhanced motion control of the throttle positioning motor, forming a compact DAQ system satisfying up-to-date demands of gas turbine measurement.

The test bench has been evaluated via numerous engine runs, which have shown the evidence of superior capabilities over the former configuration.

The system improvement cannot be considered as being finished. There exist several ways through which further development and extension could be made. For example, the authors have encountered extreme exhaust gas temperatures during starting of the engine; meanwhile turbine inlet temperature has not reflected the problem. This symptom can be explained by the insufficient air mass flow rate due to low rotor speed, but could be determined in details if at least four EGT probes would be installed in the turbine exhaust section. Improvement can be done in extending the sensor network to provide more information about engine parameters.

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