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Test Stand for the Experimental Investigation of Turbochargers with 3D Printed Components

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The paper discusses the universal test stand which allows determining the characteristics of turbochargers. Currently, there are works carried out in the world aimed to develop innovative fluid-flow machines, made partly with the use of rapid prototyping technology. This type of manufacturing technology allows reducing production time and costs in comparison to conventional methods of prototyping. This article also discusses start-up tests of the experimental test stand using a commercial turbocharger and the comparison between calculated and experimental results. In this paper, there are also described some modifications of the test stand, made prior to the start-up test, which were necessary to get more accurate characteristics of turbochargers. This work is an introduction to the investigation on turbomachines, whose elements were manufactured using the rapid prototyping technology.

Keywords: fluid-flow machines, turbocharger, rapid prototyping.

1. Introduction

Turbochargers are fluid-flow machines that have one of the highest nominal rotational speeds, which are often improved in terms of their applications and optimization [1]. Nowadays, works [2-3] on the development of high-speed microturbines are ongoing at the Institute of Fluid-Flow Machinery. These works are also carried out for turbochargers with elements manufactured using rapid prototyping methods. Increasingly, in the new literature, we can find research on modern methods for the production of machine elements [4-5], which, according to the described works, can be used in the manufacturing of high-speed machinery parts.

One of the rapid prototyping methods that are used at the IMP PAN is the MJP (Multi-Jet Printing) technology, which allows high-precision printing of plastic elements using polymeric resin. This is an inkjet 3D printing process used for printouts that require highly precise production and complicated shapes as well as serial production. Due to the low costs and time of using 3D printing technology in manufacturing machine elements, compared to conventional methods, it was decided to carry out a strength analysis of the building material. Motivation to carry out this work was finding a cheaper method for the production of prototypical elements of fluid-flow machines.

The analysis of a compressor's rotor [6] manufactured using this method allowed to assess its strength under conditions of high rotational speed (over 120,000 rpm) and it was shown that the tested rotor was able to operate properly. The next step was conducting the flow analysis at the compressor side, which allowed determining the characteristics of the turbocharger from the boost pressure side. Testing of the one side only was deliberate due to the lower working temperature at the compressor side. Further research works will be focused on using polymeric resin as a consturctional material for chosen components of the turbocharger. The working temperature at the turbine side is too high to use any elements made of a plastic material, so no tests were conducted at this side of the turbocharger.

Conventional test stands for determining the characteristics of turbochargers [7] use high-temperature exhaust gas as a power supply, which eliminates testing turbochargers with parts made of plastics. Due to the low heat resistance of the material (lesser than 88°C), it was decided to build an air-powered test stand.

This article is devoted to the description of the test stand for determining the characteristics of the turbocharger at its compressor side and to the comparison of the results of experimental tests of the commercial turbocharger with simulation results. This paper is a continuation of the work described in articles [6, 8].

2. Test stand

To determine the characteristics of turbochargers without using hot exhaust gases as a power supply to the tested machine, a test stand was designed [8] and built with the turbine supplied by compressed air [9-10]. To avoid damage to the turbine parts caused by lowering of the temperature at the turbine outlet as a result of the expansion, an in-house designed air preheater was used at the turbine inlet. This system allows one to control the inlet temperature in the range from approx. 50°C - 120°C depending on the supply pressure value, which enables keeping the temperature at the turbine outlet on a safe level (over 10°C). A commercial compressor with a maximum working pressure of 10 bar was used to supply the turbine. During the tests, the compressor was set to 8 bar. The pressure at the inlet to the turbine was controlled by an analog throttle valve, which allows for a precise control of the rotational speed of the turbine. Because the research presented in this paper was not aimed at determining the power of the turbine, there was no need to measure its mass flow rate.

A very important element of the test stand is the lubrication system of the turbocharger's bearings. In order to avoid damage to the bearings and do not cause the turbine's throttling, it was important to set the appropriate operating parameters in the lubrication system. For this purpose, an oil pump controlled by an inverter was used, which enabled the oil pressure to be kept in the range of 2.5-3.5 bar (depending on the rotational speed). An electric heater was installed in the oil tank, which was responsible for maintaining the temperature of the lubricant at the appropriate level (80-100°C).

The test stand has been equipped with sensors, allowing the measurement of selected values. At the test stand, the following measuring points were used:

- Turbine part: Air supply - temperature, pressure; Outlet: temperature,
- Compressor part: Inlet: rotational speed; Outlet: temperature, mass flow rate, pressure,
- Lubrication system: pressure, temperature.

The built test stand with measuring points is presented in Fig. 1.

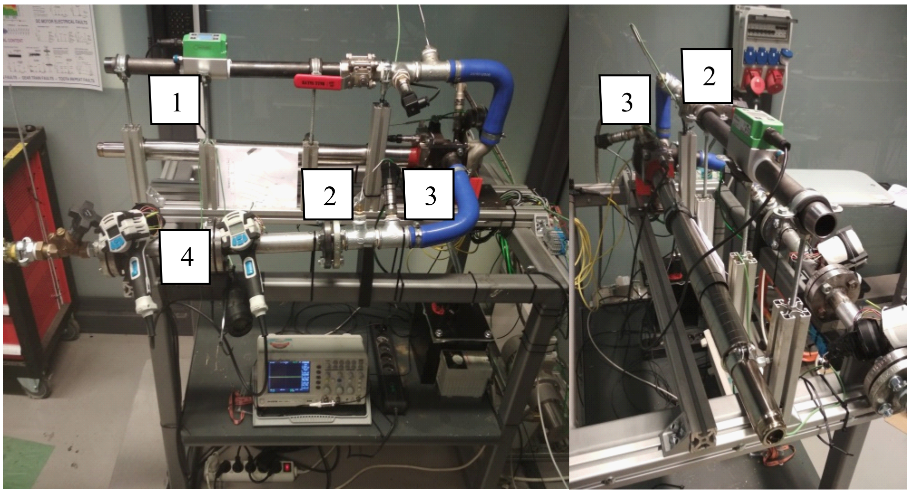

Figure 1 Test stand for determining the characteristics of turbochargers. 1 - Air flowmeter, 2 - Thermocouples, 3 - Pressure transducers, 4 - Air heater

The exhaust muffler system was also built for the test stand, due to the high noise generation. This system is visible on the right photo of Fig. 1. The compressor side has been equipped with a throttle valve to enable determination of the compressor's full characteristics.

3. Measurement system

To enable the monitoring and recording of data from the measurement points, a data acquisition system was designed and built. For this purpose, suitable sensor converters and a card for reading signals have been selected. Pressure transducers with a range of 0-16 bar (turbine inlet) and 0-6 bar (compressor outlet) in a 4-20 mA signal standard were used to measure pressure. Temperature is measured by thermocouples (mounted in the axis of the pipeline) using converters working on the Modbus RTU protocol supplied with 24 VDC voltage. The rotational speed of the compressor wheel is read using the TTL standard signal (0-5 V) optical speed sensor. The thermal mass flowmeter (which measures value only at one point) is equipped with a built-in measuring transducer, which gives on the output a current signal in the range of 4-20 mA. Two devices were used to read signals from transducers. One of them is a Modbus RTU converter, which can be connected to a measuring computer (PC) via the USB standard. The second device is the NI-6210 measuring card equipped with analog inputs and outputs as well as a pulse counter that allows determining the square signal frequency, also by using the USB connection.

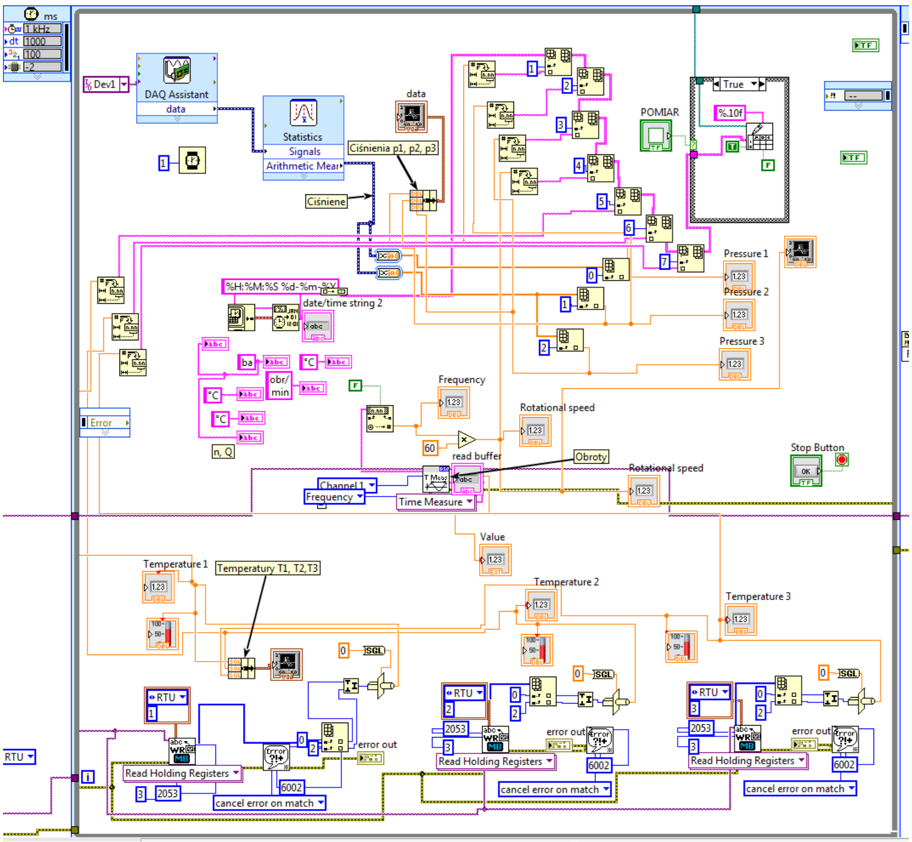

Figure 2 Block diagram of the measurement application

A data acquisition application has been created in order to be able to read and monitor the operating parameters of the turbocharger. The LabView environment was used for this purpose. The application consists of a measurement engine, which is a DAQ block that supports the measurement card module and Modbus library elements that process the signal from temperature transducers. A screenshot from the measurement application and elements of the measurement system are presented in Fig. 2.

A screenshot that demonstrates the block diagram of the measurement application is presented on the left side of Fig. 2. The upper part of the block diagram is responsible for reading data from the NI-6210 measuring card, and its lower part for reading the address from temperature transducers via the Modbus RTU protocol. The whole system operates in loop mode with a frequency of 1 Hz.

The application's UI (user interface) has been created in such a way that it is legible for the user and allows not only monitoring but also registering all operating parameters of the tested machine. In order to be able to easily locate selected sensors, a 3D diagram of the entire test stand was placed on the user's interface screen. In addition, time waveforms of selected parameters have been added on this screen. All recorded data is saved in a text file (in the form of a table, separated by tabulators). In the near future, it is planned to connect the control system to the measurement system. This will allow the automatic control of the oil pump's motor from the measuring application level. Fig. 3 presents the user's interface screen of the measuring application during operation of the turbocharger.

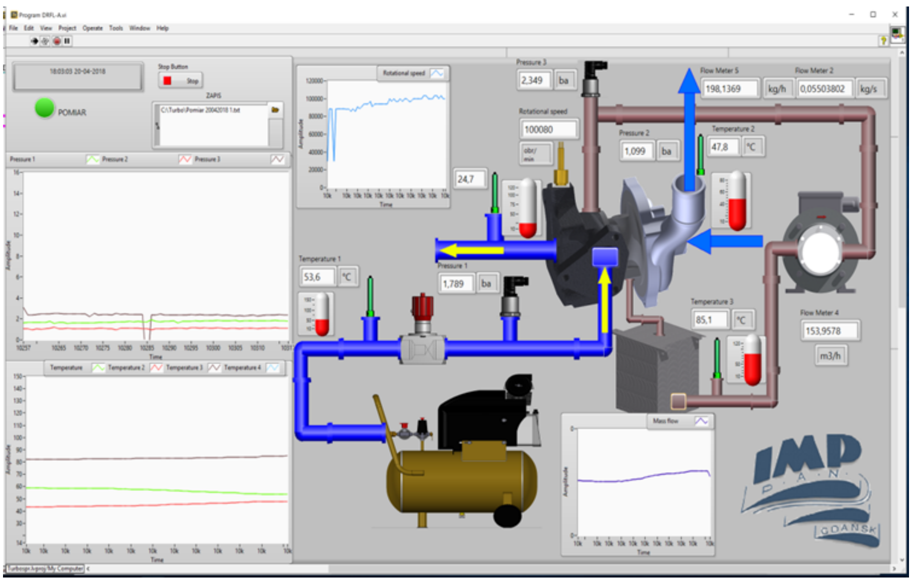

Figure 3 User interface of the measurement application during conducting research on the turbocharger (at a speed of 100,080 rpm)

4. Experimental setup and results

This investigation will be an introduction to research on a rotor made of a plastic material, which will be mounted in turbochargers. Experimental research was carried out for specific operational parameters. Despite the fact that the rotor disk is made of a conventional material, the tests were carried out as if the rotor had been made of a plastic material. Thus the measurement conditions to compare the operation of different rotors will be the same.

Before starting the tests, the turbocharger's body was heated with air at a temperature of 90°C, to make the machine more hermetic. The oil used in the lubrication system of slide bearings was also heated to 90°C, due to oil operating characteristics. The turbocharger was started and tested on the compressor side for 4 rotational speeds.

Due to the temperature increase (above 70°C) as a result of compression at the outlet of the compressor, the test has been finished at a speed of 140,000 rpm. Higher temperatures could have damaged the rotor that is made of a plastic material selected for future research.

By means of a throttle valve mounted at the compressor outlet, it was possible to set the load so that the characteristic was determined at several operating points for one rotational speed. It was decided that, for safety reasons, the air flow rate of the compressor would not drop below 0.035 kg/s (based on the simulation data), so as not to reach the limit of pumping operation mode of the turbocharger. The determined characteristics are shown in Fig. 4.

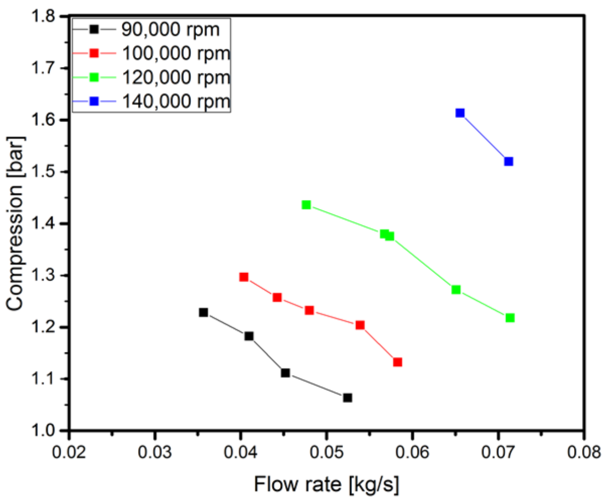

Figure 4 Experimental characteristic of the commercial turbocharger (at the compressor side) investigated on the built test stand

For three rotational speeds, values were measured at four measuring points. Due to the temperature limitation of the flowmeter at 140,000 rpm, measurements for higher rotational speeds were not possible. The results presented above were compared with simulation results for validation purposes. The simulation was carried out for the same operating parameters. The comparison of results is presented in Fig. 5. The results of the analysis were obtained for speeds greater than or equal to 100,000 rpm, so three curves were compared between each other. The simulation results are marked with dotted lines and the experimental results with solid lines.

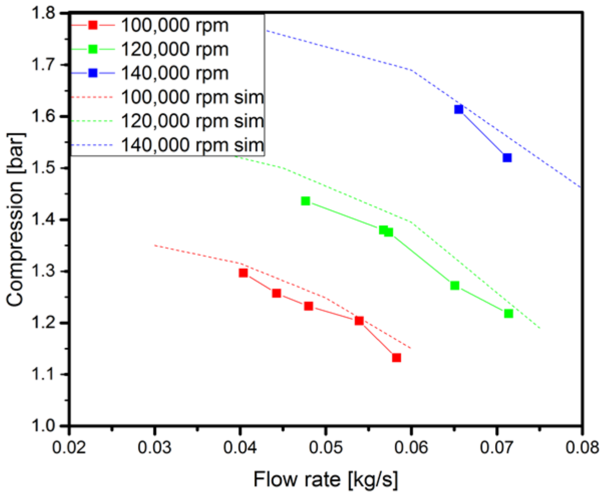

Figure 5 Characteristics of the tested turbocharger (at the compressor side) obtained during experiments and simulations (pressure vs. mass flow rate)

During the comparison of results, the smoothing and averaging of curves were deliberately not performed. The graph clearly shows the compatibility of the operation characteristics, under certain conditions, however, there are slight differences in the value of the boost pressure. Possibly those differences are caused by not taking into account (during the simulation) the gaps between the blades of the compressor's wheel.

5. Summary and conclusions

The test stand for determining the characteristics of turbochargers has been built and launched. The researches were carried out to determine the desired characteristics for a commercial automotive turbocharger under the conditions of a reduced turbine supply temperature. The correct operation of the measuring system and application used for registering and monitoring of the turbocharger's operating parameters was confirmed.

Prior to the experiment, the characteristics were determined by simulation calculations. The experimental results and the comparison of selected characteristic points for validation purposes are presented. Slight differences between the boost pressure values for tested rotational speeds may result from not taking into account the gaps between the blades of the compressor's wheel, and they will be refined in the near future.

The experimental research allowed to assess the suitability of the test stand and develop a research plan for the future (related to machine elements made of plastic). The compressor wheel was manufactured using the MJP technology and installed on the rotor. The rotor will be balanced using a high-speed balancing machine, located in the IMP PAN laboratory, and then subjected to research. Destructive testing of the rotor disk is also planned.

Acknowledgments
Simulation results were used for the validation of the experimental results. It was possible thanks to the kindness of Dr Piotr Klonowicz from the Department of Turbines (IMP PAN).

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