EXPERIMENTAL SETUP FOR TURBOCHARGER CONTROL

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Abstract: This paper presents the mechanical details regarding a new control test rig for laboratory use. A variable geometry turbocharger is this system central part. In this paper it will be shown how this rotating machine can be decoupled from the internal combustion engine and fitted in a *testbench* where a computer emulates the vehicle's motor. In order to accomplish this, a dozen of mechanical parts were designed and built. In addition, a set of sensors and actuators was adapted to the system. This article will show the final result of a system that will be used to test several different control strategies, with relevance given to the coefficient diagram method. *Copyright © Controlo 2012*

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1. INTRODUCTION

The way people travel is about to change. Since the early beginning of the twentieth century, to nowadays, the automobile has become the most prolific transportation form. The propulsion is done by an internal combustion engine which convert thermal energy, by burning diesel or petrol, into mechanical energy. However, due to several reasons such as economical, environmental among others, there is a tendency to replace the internal combustion engine by electrically powered motors. Electrical motors have many interesting properties. One of them is its efficiency. An electric motor can easily reach an efficiency above 80% against the average 40% for internal combustion engines. Nevertheless, at the present, there are serious limitations regarding electric engine cars proliferation. Their acquisition cost and autonomy are still two major restrictions. Even if the former aspect can be attenuated by proper tax reduction policies, the later is strongly dependent of technical issues, i.e. the development of faster charging methods, longer life batteries, etc.

In order to circumvent some of this operational aspects, hybrid vehicles, that combining thermic engines with electric propulsion, begin to be available in the market. Currently some of the major car manufacturers are selling hybrid cars, such as: Toyota Prius, Honda Jazz, Citroën DS5, Peugeot 3008 Hybrid, just to mention a few.

An important thing to note is that, at least for now, the internal combustion engine will not be completely overhauled by its electric counterpart. They will coexist until all the major electric car issues are completely solved. Since the Diesel engine is more efficient than the Petrol one, the former is a stronger candidate to be incorporated into hybrid autos. However Diesel motors requires larger air mass than their counterparts for the same engine cylinder volume. In order to do that, modern Diesel motors are coupled to a rotating machine that compress the engine inlet air inside the cylinders. This rotating machine, usually a turbocharger or supercharger, is colloquially known as Turbo.

2. TURBOCHARGING OVERVIEW

A turbocharger is nothing more than an air compressor driven by the kinetic energy of exhaust gases. His internal structure is composed by two wheels, the compressor and the outlet turbine. Both are mechanically coupled via a shaft. Figure 1 represent a turbocharger cartridge, showing two wheels: the compressor impeller (left side) and the turbine (right side). Exhaust gases kinetic energy are used to spin the outlet turbine and, due to the mechanical coupling between the two wheels, the centrifugal compressor also turns with the same rotation speed.

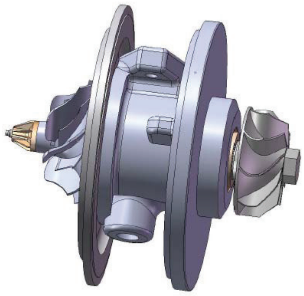

Fig. 1. Picture of a turbocharger cartridge. The left wheel concerns the impeller and the right one is the turbine.

The main turbocharger objective is to improve the engine volumetric efficiency. This is done by increasing the intake air density. During his rotation, the centrifugal compressor absorb air at ambient pressure (approximately 100 kPa) and increases it pressure, around 140 to 160 kPa, before it enters the intake manifold. With this strategy, at each intake stroke, larger air mass enters into the cylinders. This air mass increase improves the vehicle performance in several ways: torque increase and fuel efficiency are two of them.

Due to the different engine regimes, and since there is a indirect mechanical link between the crankshaft and turbo rotor angular velocity, modern turbochargers are internally equipped with strategies in order to regulate inlet air pressure for distinct engine rotations. This kind of machines are designated by variable-geometry turbochargers.

Among other approaches, a variable-geometry turbocharger possesses a set of vanes in the exhaust housing in order to maintain a constant gas velocity across the turbine. Figure 2 presents the nozzle image of the turbocharger used in this setup. An external ring mechanically synchronises all the internal vanes and his angular position are controlled externally by a lever.

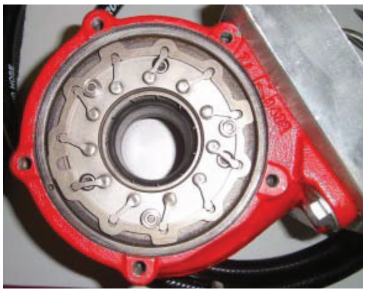

Fig. 2. Internal aspect of the "*hot*" part of a GT1749 variable-geometry turbocharger. Each of the eleven small levers controls a vane.

Usually this lever position is changed by a pneumatic actuator. The pneumatic signal used to control this actuator is modulated by the Engine Electronic Unit (ECU). By gathering the information collected by an array of sensors, for example the mass air flow sensor (MAF) and crankshaft sensor just to name a few, the ECU is able to compute the "ideal" turbocharger rotation.

Sometimes other components are added to improve the turbocharger efficiency. One of them is the inter-cooler. When air is compressed, it heats and expands. Hence a part of the pressure increase results from heating the air before it goes into the engine. This pressure increase is not accompanied by increased air mass. The inter-cooler objective is to transform hot air at a given pressure to cold air at the same pressure since cold air is denser than hot one.

Computing the exact turbocharger size for a particular engine is a multi-criteria problem. There is always a tradeoff between engine power, fuel consumption and political environmental impositions. This problem is way outside the scope of this paper. Indeed, the major motivation of this work is to test a particular control strategy for angular vanes regulation on a variable-geometry turbocharger. This system has multiple operating points with different dynamics including many non-linearities. Due to usual simplifications used in the models, for this work one has decided to build a control rig having, in it's core, a true comercial turbocharger: the Garrett's GT1749v turbocharger scavenged from a Renault Laguna 1.9 DCI (120 hp). The system, that will be discussed in the following sections, will be used as a test bench for several different control algorithms.

3. THE TURBOCHARGER RIG

In order to operate, a turbocharger must be coupled to an internal combustion engine. However, for experimental purposes, acquiring and running an engine inside a laboratory has severs drawbacks. First of all economical since it is necessary to buy and maintain the engine and modify a room with proper soundproofing, ventilation, etc. So one has devised a way to replace a true engine by a mathematical model while maintaining a real turbocharger. A 3D model of the system rig initially envisioned is illustrated in figure 3. The exhaust gases that make the turbocharger spin are replaced by compressed air. In the referred figure the inlet pointed by number (6) concerns the turbine compressed air intake. The kinetic energy stored in compressed air is used to turn the turbine. Upstream the compressor input port a mass air flow (MAF) sensor is installed and the air pressure exiting port (3) is measured by a sensor.

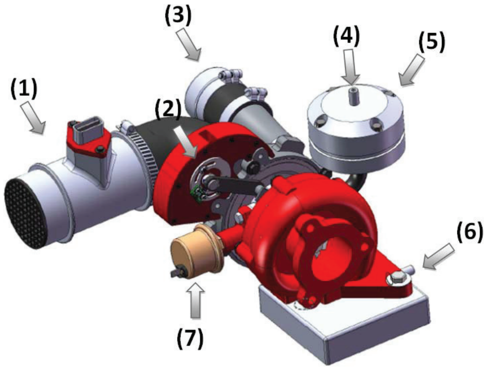

Fig. 3. The model of the turbocharger rig. (1) MAF sensor, (2) stepper motor, (3) compressor outlet, (4) compressing air intake, (5) diaphragm pump, (6) compressor air turbine inlet, (7) Oil pressure sensor.

Other original turbocharger modification was the replacement of the pneumatic actuator by a stepper motor. The electronic control of a stepper motor is simpler and more precise than the pneumatic counterpart. In this setup a "*tin can*" stepper motor with 7.5°of resolution was used. The motor axis was mechanically linked to the vanes control lever.

One of the major challenges was to devise a way to maintain oil under pressure inside the turbocharger gasket. The reason of this requirement is due to the turbo mechanical conception: the rotor friction is reduced, not by ball bearings, but by journal bearings. This kind of bearing need constant oil under pressure to ensure proper operation. In order to solve this problem, and to avoid a electrical or mechanical pump, a diaphragm type pump was designed. In this case the oil does not flow inside the turbocharger. It remains static at a pressure regulated by the compressed air pressure applied to the input port (4).

Since a fail in the bearing can rapidly cause rotor wear a oil pressure sender (7), in this case the FAE14540, was fitted into the oil circuit. Oil pressure needs to be between 275 and 310 kPa at the maximum engine operating speed (Bell, 1997). This and all the other sensors used will be described in detail.

4. WORKPIECES

The aim of this section is to document the process used to build the custom made parts that will be assembled into the turbocharger. First of all, all the workpieces were tailored from compact aluminium blocks using a computer numerical control machine (CNC). The 3D models, drawn in SolidWorks®, were used to derive the CAM files which, in turn, control the CNC milling cutters. The photographs presented in Figure 4 illustrate the milling process. In the left a picture of the CNC machine used in the manufacturing process: a Dekel Maho DMC 63V. In the right a detail of an almost finished piece (in this case one of the stepper motor fittings).

Fig. 4. The milling process: at left the CNC machine used to cut the pieces and, at right, an example of a machined assembly part.

More than a dozen parts were designed and built. Some of them using a machine-tool. The rest using the computer numerical control machine mentioned above.

Figures 5 and 6 illustrates some of the more challenging parts built. The first of them represent the stepper motor housing. This part will be attached to the turbocharger "cold" side and is composed by three pieces. The ring represented in the assembly top will be used to define the stepper zero position. This position information will be sent to the data acquisition card by a Hall switch mounted over this ring.

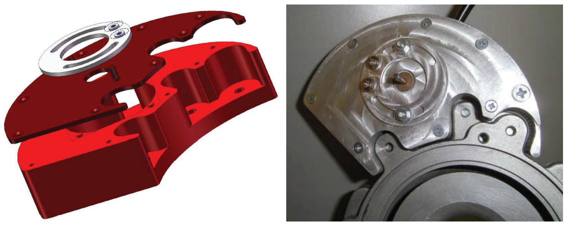

Fig. 5. The stepper motor housing assembly. In the left an exploded view of the 3D model and, at right, the referred part already fitted in the turbocharger.

Figure 6 show a seccional cut of the oil pump devised. Compressed air enters the upper chamber and transmit pressure to the oil chamber through a diaphragm.

The final system, completely assembled, is represented in Figure 7.

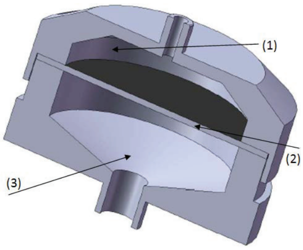

Fig. 6. Seccional view of the oil pump. (1) compressed air chamber, (2) diaphragm, (3) oil chamber.

Fig. 7. The turbocharger completely assembled.

The following section describes the main characteristics of some of the used sensors. More specifically the mass air flow sensor, the oil and air pressure sensors.

5. SENSORS AND CALIBRATION FUNCTIONS

Correct engine operation lays on information provided by an array of multiple sensors scattered throughout the automobile. In the devised setup some of the sensors are real and others are emulated by software (during engine operation). In this work the following variables are effectively measured:

- Turbocharger rotation speed;
- Intake air temperature;
- Turbocharger air mass flow;
- Outlet air pressure;
- Oil pressure.

The turbocharger rotor speed is measured using a Hall sensor switch mounted near the turbine center where a magnet was placed. The information regarding intake air temperature is provided by a 10K NTC thermistor. The air mass flow measure is taken care by a Bosch 0 281 002 421 MAF, the outlet air pressure is measured by Honeywell's AWM330V and the oil pressure by a FAE14540. These last three sensors operation will be described below in greater detail.

5.1 *The Mass Air Flow Sensor*

In electronic fuel injection engines, the vehicle ECU depends on the information provided by the mass air flow sensor to compute the exact amount of fuel to be delivered to the engine cylinders. In the present setup the ais mass flow is sensed by Bosch's 0 281 002 421 air mass meter. This sensor, based on hot-film technology, provides a voltage proportional to the air mass flow. The sensor external aspect is illustrated in Figure 8 and his calibration curve is presented in Figure 9.

Fig. 8. External aspect of Bosch's hot-film mass meter.

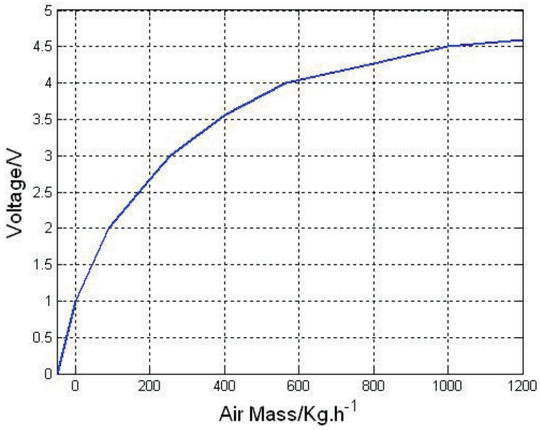

Fig. 9. Calibration curve for Bosch's hot-film mass meter.

It was possible to approximate the calibration curve, with a relative error of less than 3% using the following function:

$$v(\phi) = v_1(\phi) - v_2(\phi) + 2.033 \qquad (1)$$

where ϕ refers to the air mass flow in $kg \cdot h^{-1}$, v a voltage in Volts and,

$$v_1(\phi) = 0.475 \cdot \log(0.036\phi + 3.19) \qquad (2)$$

and

$$v_2(\phi) = 1.43 \cdot \exp(0.262 - 0.00342\phi) \qquad (3)$$

5.2 *The Oil Pressure Sensor*

The oil pressure inside the turbo cartridge is measured using the FAE 14540 sensor. This is a resistive type sensor capable to measure pressures in the rage from 0 to 1 GPa. Figure 10 illustrate the external sensor aspect.

Since the sensor is specially designed for automotive application the fitting is done through a 12 mm/ 1.5 mm screw and one of the resistor poles is the sensor metallic housing.

Fig. 10. External aspect of the FAE14540 oil pressure sensor.

From the data provided by the manufacturer it is possible to see that the calibration curve standard deviation was too high, i.e. there are major differences in the sensor electric characteristics after the manufacturing process. For this reason a new calibration curve was derived as shown in Figure 11.

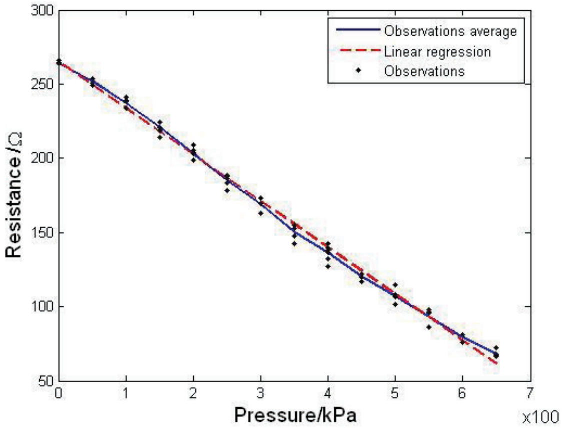

Fig. 11. FAE14540 calibration curve.

The relationship between the sensor output resistance R and oil input pressure P, expressed in kPa, can be modelled by the following first order parametric equation:

$$R(P) = -0.313421 \cdot P + 265.1024 \qquad (4)$$

From the measured data, and taking into consideration that the oil pressure will be between 150 and 250 kPa, the modelling error is lower than 5%.

5.3 *The Air Pressure Sensor*

The air pressure, at the turbocharger outlet, will also be measured. In this case the HCX005 from Sensor Technics is used. This sensor already integrates the signal conditioning stage and has the appearance illustrated in figure 12.

After proper polarization, the relationship between air pressure and output voltage is described by the following equation:

$$v(P) = \frac{4}{500}P + 0.5 \qquad (5)$$

where v is the sensor output voltage expressed in Volt and P is the air pressure in kPa.

Fig. 12. External appearance of the HCX005 air pressure sensor.

6. PUTTING IT ALL TOGETHER

In this last section the interface between the experimental setup and the digital controller is explored. First of all the input/output variables will be handled by a data acquisition card (DAQ). In particular we are talking about the USB6008 from National Instruments. The I/O data acquisition ports will be linked to the sensor outputs (after proper signal conditioning of course) and to two actuators: the stepper motor and a proportional pressure valve. Once again both actuators are connected to the DAQ by custom made power interfaces.

As mentioned before, the stepper motor will be responsible for change the turbocharger geometry. On the other hand, the pressure control electro-valve will be used to model the different engine regimes. By changing the kinetic energy of the turbine input air one is able to emulate the changes in exhaust gases due to different motor operating conditions.

On the other DAQ end, the information flow will be transmitted, by USB protocol, to a ordinary personal computer (PC). This machine will be responsible to take the information provided by the sensors and produce a set of actuator orders. Figure 13 illustrates the overall system architecture.

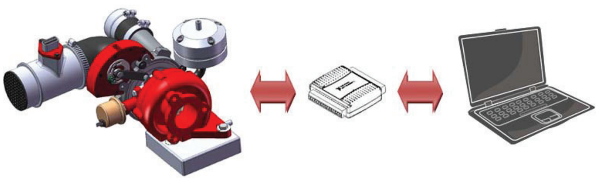

Fig. 13. The data acquisition and control system setup devised.

Communication between the PC and the DAQ will be handled by the National Instruments software LabVIEW®. LabVIEW® is a dataflow oriented programming platform (Wells and Travis, 1996). This platform is programmed using a graphical formulation instead of the usual text based format. For this reason, the LabVIEW® programming language is designated by “G”. Developing graphical interfaces for SCADA based software is very simple and straightforward. A large set of gauges, dials, LEDs, displays and graphics are easily integrated into the program. Figure 14 present the current *frontend* aspect of the turbocharger software developed in LabVIEW®.

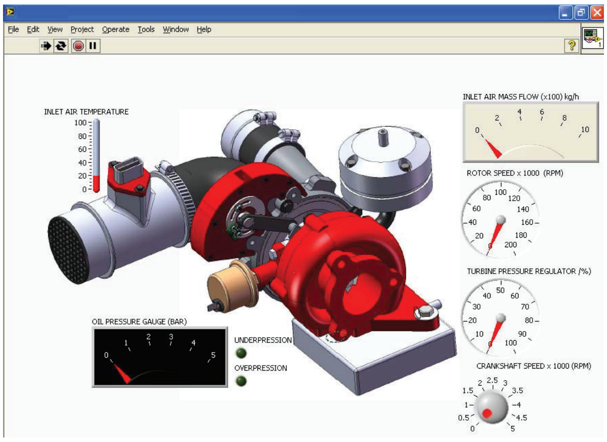

Fig. 14. Turbocharger system *frontpannel* developed in LabVIEW.

Besides this graphical user interface, the software must also emulate the engine operation and do all the math regarding the controller.

7. CONCLUSIONS AND FURTHER WORK

This paper has presented the mechanical details regarding a new control test rig for use in the laboratory. The experimental setup has, as central part, a real variable geometry turbocharger. This rotating machine is coupled to a computerized system for supervising and control. In this design the turbocharger operation was changed in order to decouple it from the internal combustion engine, i.e. now the kinetic energy used to rotate the turbo is derived from compressed air instead of engine exhaust gases. Using this strategy the multiple engine regimes can be software emulated. The simulation results will be used to modulate a pneumatic pressure regulator.

Another change concerns the replacement of the pneumatic actuator, responsible for turbocharger geometry change, by a stepper motor. With this strategy one gets a more precise and easy to control actuator. In addition a oil pump had to be designed and fitted for proper bearing operation.

For all these changes to take place one had to design and build a set of mechanical parts. In addition, sensors and actuators had to be selected and associated to the system. Therefore, in parallel to the mechanical system development, signal conditioning and power electronics circuits had also been designed and built.

With the completion of the electromechanical part of this project, one will persecute the following objectives:

- Obtain, test and validate an engine model. There are extensive bibliography on this subject. For example (Rizzoni, 1986) and (Feilong Liu and Soliman, 2012);
- Develop and tune a digital controller using the Coefficient Diagram Method, a method developed in the beginnings of the 1990's by Manabe (Manabe, 1998) (S.E. Hamamci and Manabe, 2002). The objective is to design a robust controller for outlet pressure regulation, as a function of turbo's geometry, and for multiple engine regimes.

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