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Experimental analysis on the performance of a turbocharger compressor in the unstable operating region and close to the surge limit

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ABSTRACT

To make simulation models able to accurately predict engine performance, a better understanding of compressor behavior over an extended range can be accomplished by using a specialized test facility and measuring equipment. Besides, the correct surge line position is another important aspect to be considered to optimize engine-turbocharger matching calculation. In the paper the results of an experimental investigation developed on a turbocharger compressor for heavy duty vehicle application is presented. The study was focused on the definition of surge line position adopting different methods and on the evaluation of compressor performance over an extended range, taking into account compressor behavior both in the stable and unstable operating region.

1. Introduction

The environmental impact and energy demand of road vehicles have recently become more significant, justifying the great effort to develop technological solutions to limit pollutant emissions while reducing engine fuel consumption, according to the requirements of the recent European Commission Regulation on the carbon dioxide emissions for new registered passenger cars [1]. The goal of CO_2 reduction contributed (especially in Europe) to an increasing market share of automotive diesel engines thanks to the introduction of several technologies, such as fuel direct injection, turbocharging systems fitted with advanced control devices [2,3], electronically controlled fuel injection systems and new exhaust system layout [4–6], with particular reference to after-treatment devices. On the other side, the need to reduce CO_2 emissions to enhance fuel economy in automotive spark ignition engine led car manufacturers to introduce different advanced technologies to be jointly adopted [7,8]. Among them, turbocharging technique in conjunction with the downsizing concept seems to be the most promising way to achieve this target. However, a successful application of exhaust turbocharging to downsized engines must overcome various difficulties, related both to the specific operating environment (exhaust gas temperature level) and to engine performance, focusing on low-end torque and transient response. Dedicated investigations on the turbocharging system are therefore necessary in order to get a better understanding of its performance, particularly in the typical unsteady flow conditions occurring in the intake and exhaust circuit of automotive engines. The one-dimensional model, generally adopted to compute the engine-turbocharger matching calculation, requires several information on turbine and compressor behavior [9–11]. Several difficulties have to be overcome in order to minimize the inaccuracy of the calculation. For example, only steady flow maps are generally provided by turbocharger manufacturer hence causing errors in the evaluation of turbocharger behavior under real operating conditions.

As regards the turbine, manufacturer steady flow maps are generally defined over a restricted operating range and the effect of the regulating device on turbine performance is not taken into account if a waste-gate valve is fitted [12,13]. Besides, unsteady flow performance of both turbine and compressor must be considered in order to take into account the effect of pulsating flow generated by engine valves opening and closing [14–19].

As regards the turbocharger compressor, some limitations are related to the definition of performance maps, generally not defined over an extended range. Besides, surge phenomena are affected by circuit volume which is generally different from the automotive intake circuit geometry. Another important aspect to be taken into account is the sensors location along the circuit, as it influences the efficiency levels experimentally evaluated. As a consequence, deep experimental studies on the compressor performance under both steady and unsteady flow conditions are needed, with particular reference to the surge limit. To this purpose, measurements performed on fully flexible test facilities can

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Nomenclature

Definitions

- c_p specific heat at constant pressure
- n_{cr} compressor corrected rotational speed
- n'_t turbine rotational speed factor
- M_{cr} compressor corrected mass flow rate
- β_{cTT} total-to-total pressure ratio
- η_{cTT} total-to-total efficiency

Notations

- a sound speed (m/s)
- k specific heat ratio
- n rotational speed (rpm)
- p pressure (bar)
- r radius (m)
- A area of compressor downstream pipe (m^2)
- L length of compressor downstream pipe (m)
- M mass flow rate (kg/s)
- P power (kW)
- R gas constant (kJ/kgK)
- T temperature (K)
- U speed at blade tip (m/s)
- V volume between compressor and downstream valve (m^3)
- β compression ratio
- ε expansion ratio
- η efficiency

Subscripts

- 0 reference condition
- 1 compressor inlet section
- 2 compressor outlet section
- 3 turbine inlet section
- 4 turbine outlet section
- c compressor
- in,av impeller inlet, average between tip and hub
- m mechanical
- out impeller outlet
- s isentropic
- t turbine
- S static condition
- T stagnation condition

supply a lot of information to be used both in the development of simulation models and to assess correlation criteria between steady and unsteady turbocharger operation for automotive engine application. A turbocharger test rig is available at the University of Genoa [13,15], which allows to perform investigations on automotive turbocharging systems both under steady and pulsating flow conditions. In this work the definition of surge-line position of a turbocharger compressor for heavy duty vehicle application is analyzed. As above mentioned, this aspect is particularly important in order to optimize engine-turbocharger matching calculation. Actually, surge operation can limit boost pressure capability at low engine speed and high load region (low end torque). Therefore, in order to extend the torque range and attain good transient response, it is necessary to analyze the compressor behavior at low flow rate levels. In this paper different measurements related to compressor performance in the stable and unstable zone are reported with particular reference to the surge phenomena. In a first step of the analysis, steady flow maps were measured from the choking region to the surge line, taking into account different methods to identify deep surge phenomena. The experimental investigation was then extended by exploring compressor curves on the left side of the surge-line. An extended definition of compressor performance maps can help to reduce the typical extrapolation errors within engine-turbocharger matching calculations especially when simulating engine transients.

2. Methodologies

A short description of the experimental facility operating at the University of Genoa is reported in this section, referring to the main characteristics of the test rig and the measuring system, finally summarizing the experimental program.

2.1. Experimental test rig and measuring equipment

The activity was carried out at the turbocharger test facility of the University of Genoa (Fig. 1), which is a cold-air apparatus which allows to perform investigations on intake and exhaust automotive components under both steady and unsteady flow conditions. Measured quantities presented in the paper were therefore scaled using the conventional non-dimensional groups (in order to take account of different gas density with respect to the real operation). Dry clean compressed air is delivered by three different compressors that can supply a total mass flow rate of 0.6 kg/s at a pressure level of 8 bar. Thanks to the availability of two separate feeding lines, it is possible to measure turbocharger performance over an extended range by properly control the upstream pressure level of each circuit. Turbocharger compressor can also suck air from the ambient through a filter. The turbine feeding line is fitted with an electrical air heater to raise the air temperature up to 400 K. A more detailed description of the test bench is presented in [13,15,20].

Even if experimental investigation was performed at low air temperature at the turbine inlet, both turbocharger and the relevant connecting pipes were thermally insulated to estimate with

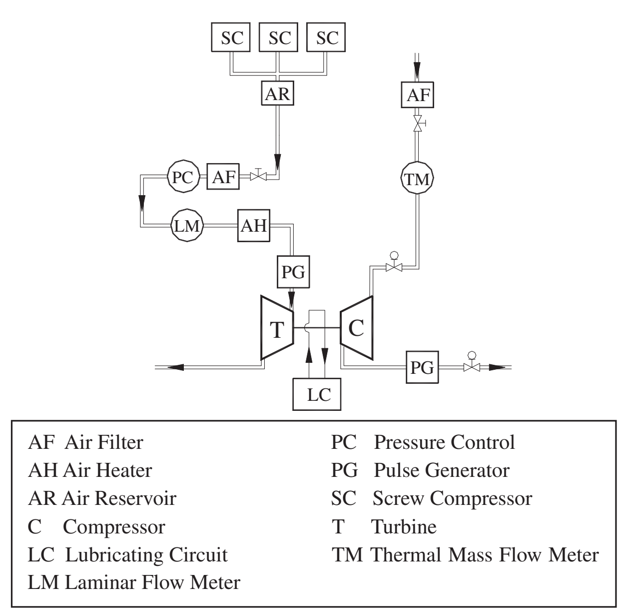

Fig. 1. Schematic layout of University of Genoa turbocharger test facility.