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Automotive compressor: effect of an electric throttle in the upstream circuit on the surge limit

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Abstract. On vehicles equipped with a turbocharged engine, there is a risk of compressor surge. This surge generates instabilities that lead to driving inconvenience, or even mechanical failure of the supercharging system. In general, the surge appears rather in transient operation: sudden closing of the throttle valve on gasoline engine, regulation of the EGR on diesel engine linked also to turbine regulation (VNT device or Waste Gate). On a turbocharger test stand, we set up the surge line in a "conventional way": stationary experiments. Then we set up this line in transient conditions for different positions of an electric throttle placed upstream the compressor. It appears that: the surge limit is pushing back to lower flow rates when it is determined in transient; the surge limit is pushing back to lower flow rates when closing the throttle valve. The tests were carried on by the transient analysis of the surge during a quick closing-opening of the electric throttle valve**.**

1 Introduction

Most automotive engines are turbocharged to reduce CO_2 emission and fuel consumption. On an automotive engine, the manufacturer ensures that the engine operates out of the surge phenomenon zone of the compressor in stationary regime. To achieve this condition, the manufacturer keeps a margin from surge limit defined by the turbocharger supplier. This margin can be more or less important according to the manufacturer's skill and knowledge.

In the case of vehicles, if the automotive manufacturer has correctly set the surge margin for steady operation, the appearance of surge will concern only transient engine regimes, or when control systems are activated (throttle vane, EGR, bypass of fixed geometry turbines, nozzle vane of variable ones...).

The surge limit has been researched in numerous studies seeking to determine a criterion to detect the occurrence of surge [1, 2] but also on the validity of this limit on engine operation. These studies were mainly carried out for stationary operating regimes.

Phenomena leading to surge instabilities complicate the study of surge occurrence which may be associated to the compressor stall and may achieve a mild surge depending on the circuit acoustic resonance. For a high rotational speed of the compressor, the limit is difficult to characterize, and it is possible to switch abruptly to a deep surge [3, 4].

In order to use turbochargers in a larger operating range, it is necessary to determine precisely the surge limit and to identify mild surge and deep surge [5-8]. Sinusoidal signals of pressure ratio or mass flow rate characterize the deep surge and may be a better criterion for identifying the surge limit [9,10]. Other methods as the analysis of the standard deviation of temperature signals [11] or frequency domain analysis [12, 13] have also been applied on automotive turbocharger performances studies. Real-time quantification of the surge margin associated with an appropriate control would achieve the best performance of the system while maintaining stable operation, but it is still a challenge [3, 4].

After presenting the test bench, procedures for determining surge limits in stationary and transient tests are explained. The surge limits are compared.

Transient surge limits are also compared for different openings of an electric throttle placed upstream the turbocharger.

Finally, appearance of surge is studied for a quick closing of the throttle valve.

2 Experimental set-up

2.1 Test bench description

A prototype compressor from Valeo has been used for the purposes of this experimental study.

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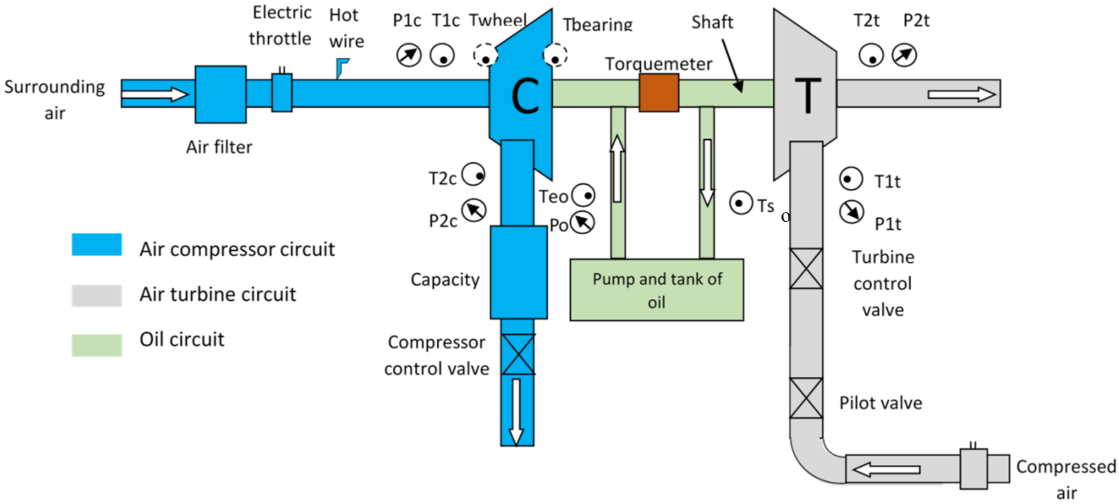

Fig. 1. Diagram of the test bench.

The characteristic curves for this compressor have been measured. In order to evaluate precisely the power at the output of the wheel, a dedicated torquemeter has been installed between the compressor and the compressor drive turbine.

On the downstream circuit, a 5L capacity is integrated to amplify the surge phenomenon and to make it easier to detect [14]. A diagram of the test bench is presented in Fig. 1. In this study, only the downstream circuit has been modified.

Experimental parameters have been measured using classical sensors (piezoresistive pressure sensors, PT100 wires probes). For measurements occurring in deep surge, a temperature sensor, Twheel, is added just upstream the compressor wheel using a K thermocouple with a diameter of 0.5 mm. The flow rate is measured with a hot wire probe upstream the compressor. The hot wire mass flow sensor was calibrated using the information given by a thermal mass flowmeter [14].

The valve placed upstream the compressor is an electric throttle usually used on turbocharged Diesel engines (Fig.2). This component is powered with 12V using the PWM (Pulse Width Modulation) method by the ECU device (Engine Control Unit).

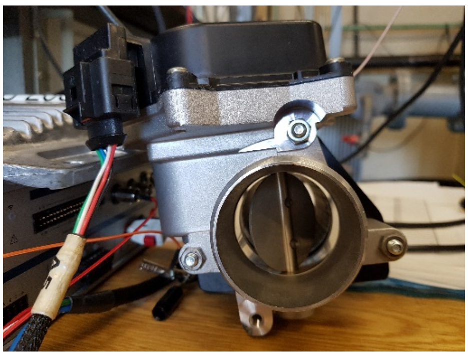

Fig. 2. Electric throttle.

The opening of this valve is controlled by a 0-5V signal. A Hall effect position sensor powered with 5V allows for the control of its position. For the transient measurements, a Producer-Consumer type loop is developed with the Labview software in order to be able to simultaneously control the valve and acquire signals.

An example of control signal (red line) and of the position signal (blue line) is presented in Fig. 3. The valve is fully opened for 4.5V and fully closed for 0V.

The control is generated by a PID module in Labview. In the experimental measurements presented in this paper, the voltage values of the control are given in the form of a table, see Fig. 3. The position follows the control for 0.2s delays. Below this value, a time lag is created.

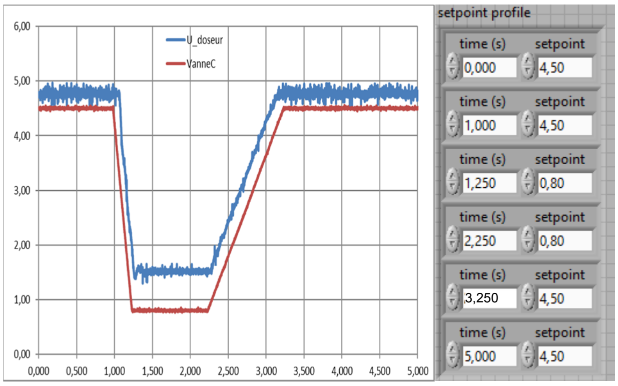

Fig. 3. Control signal and position signal of the electric throttle.

2.2 Definition of the surge limit in stationary test

The surge limit is determined by the operator from the noise generated once it occurs or by the signal analysis (for example, pressure, temperature, flow rate…). This limit depends on upstream and downstream conditions in the compressor circuit. In our experimental set-up, the geometry is the same for all measurements. The signal used in this paper is measured with the hot wire anemometer as it seems the most sensitive sensor to surge. We have defined two surge levels: the appearance of the surge, called mild surge and the deep surge. The mild surge is identified with a Fast Fourier Transform (FFT) analysis of the signal when a frequency peak occurrence (Fig. 4 (b)). The raw signal presents some regular fluctuations (Fig. 4 (a)). The deep surge corresponds to a very high peak of frequency detected by the Fourier analysis (Fig. 4 (d)). In this case, the raw signal has a sinusoidal shape as it is shown in Fig. 4 (c).

In order to draw this surge limit, we adjust the rotation speed for a first point at low regime. Next, we close gradually the valve at the compressor outlet until mild surge appears. If the rotation speed is too high, we adjust the working point by reducing the turbine velocity acting on the turbine control valve. The point where the surge phenomenon appears is then acquired. The compressor valve is closed again until the deep surge and the working point are recorded. Finally, the same process is applied for another rotation regime.

The appearance of the surge and the deep surge have been determined for a full opened position of the electric throttle valve. The determination of these limits follows these steps: the valve placed downstream the compressor is closed to operate in proximity to the surge limit. This position is evaluated from previous results when measurements were conducted in iso-speed conditions.

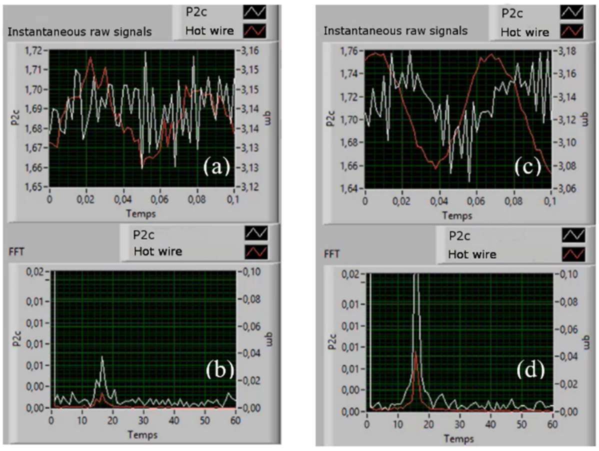

Fig. 4. Raw signals of instantaneous pressure in outlet of the compressor (red line) and flowrate (white line) for (a) the mild surge and (c) the deep surge and corresponding FFT signals calculated on same signals respectively in case of (b) mild surge and (d) deep surge.

Measurements have then been repeated for other rotation speeds to build surge limits presented in Fig. 5.

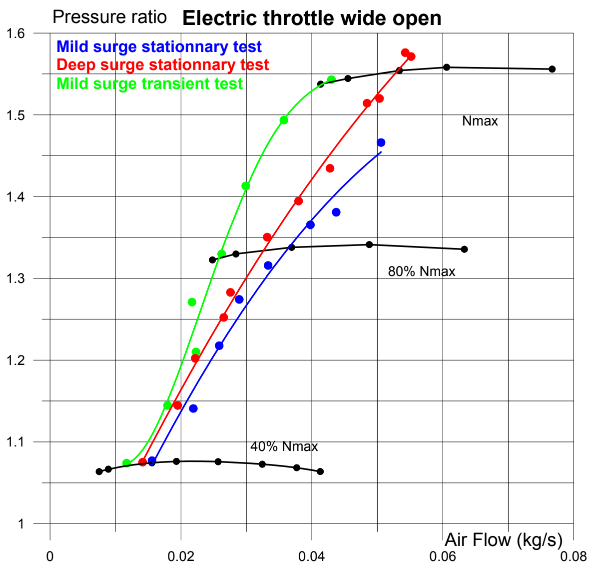

Fig. 5. Comparison of surge lines obtained in stationary and transient tests.

2.3 Definition of the surge limit in transient test

The setup of this line is carried out as follows: for a selected rotation speed, the valves after the compressor and before the turbine are adjusted to set an operating point close to mild surge. Then the compressor downstream valve is progressively closed until deep surge is achieved. Data are recorded for a duration of 5 s at 1 kHz acquisition rate.

Fig. 6 presents the evolution of air flow and the pressure downstream the compressor P2c for an initial speed close to 80% Nmax.

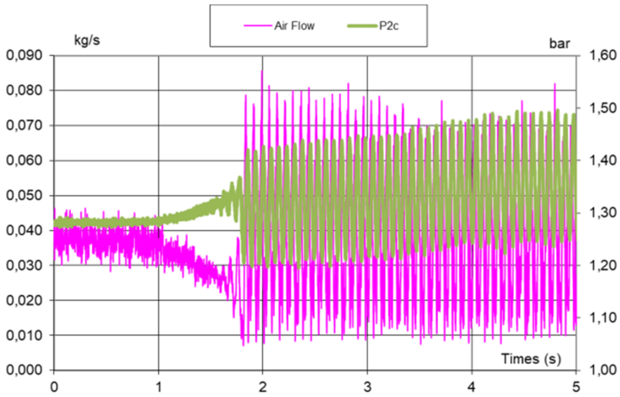

Fig. 6. Evolution of Air Flow and relative pressure downstream the compressor P2c versus time.

The beginning of the surge is determined from the RMS (Root Mean Square) or SD (Standard Deviation) calculation of the air flow signal. The SD shows a greater sensitivity [14] as shown in Fig. 7.

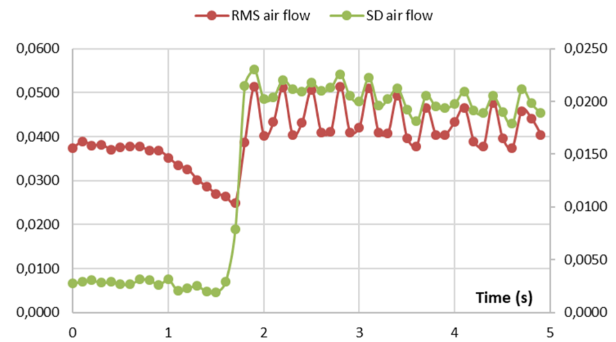

Fig. 7. RMS and SD of Air Flow versus time.

The tests are then repeated for other speeds and openings of the electric throttle thus making it possible to construct the surge limits of Fig. 8.

3 Surge limits comparison

Fig.5 shows the surge lines obtained for a wide-open position of the electric throttle. The surge lines obtained in the stationary test for mild surge and deep surge are logically slightly offset. On the other hand, a clear difference exists between the lines of mild surge obtained for stationary and transient tests. A margin on air flow of about 30% is earned at 80% of Nmax. This difference may be related to the aerodynamic inertia of the fluid column.

Nevertheless, this limit seems more representative of what actually happens during the transient operation of an automotive engine. This would allow the engine to operate briefly beyond the stationary surge limit without any inconvenience for the driving, thus increasing the low speed torque.

Fig. 8 shows the results obtained for different positions of the valve of the electric throttle.

The results of these tests show that the closer the electric throttle valve, the lower the surge limit. This confirms previous results obtained during tests on the effect of an upstream valve [14]. A margin of more than 60 % is obtained between the open position and the position $U = 1.0$ V.

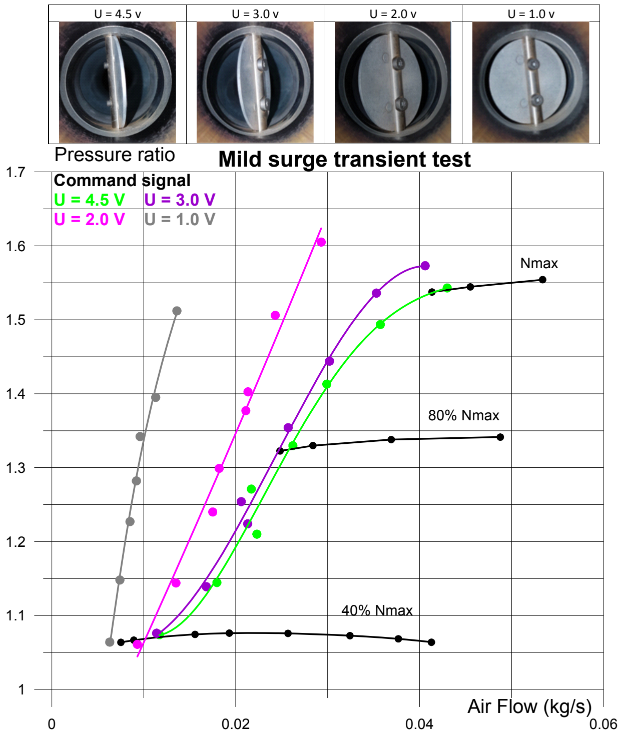

Fig. 8. Comparison of surge lines obtained in transient tests for different openings of the electric throttle.

4 Surge limit evolution closing-opening

Some experiments have been carried out for closing and opening of the electric throttle. Different sets of profiles have been performed from a wide open initial position and a compressor speed close to 80% of Nmax. For this speed, the opening of the valve downstream the compressor is set to obtain a point close to the mild stationary surge line.

Test results presented are for setpoint profile according to Fig. 3. The measurements are recorded for 5 s at a data acquisition rate of 1 kHz. The turbine pilot valve being fixed, compressor speed increases when closing and decreases when opening, as shown in Fig. 9. Special care is needed during experiments to avoid overshoot of Nmax.

The results of the measurements are presented in Fig. 10. It is possible from this figure to extract the surge loop with a time step of 0.025 s. In Fig. 11 some surge loops are presented for different initial time.

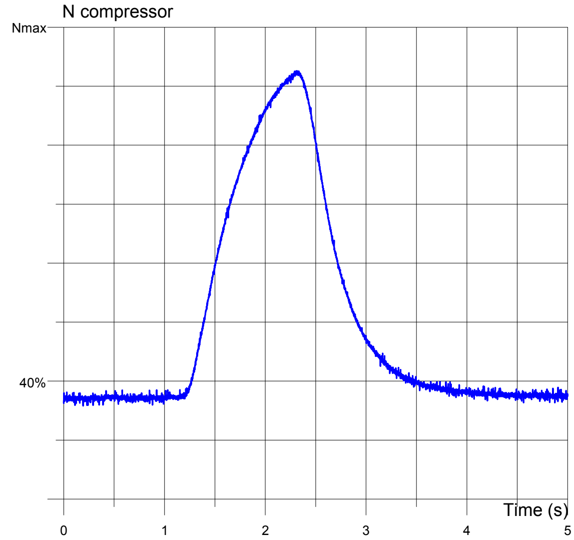

Fig. 9. Speed evolution during closing-opening.

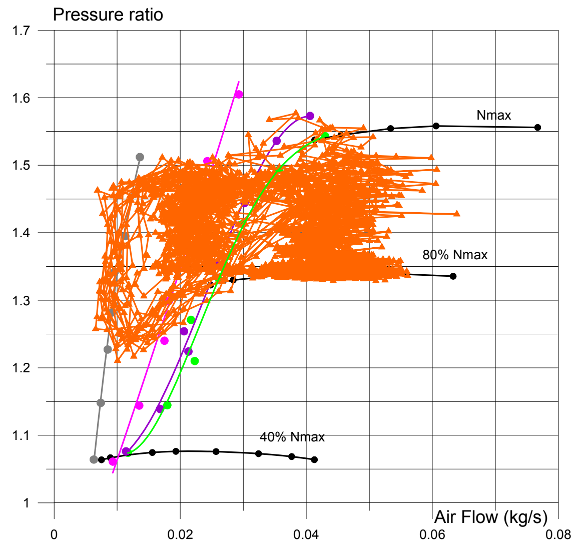

Fig. 10. Air Flow and Pressure evolutions during closing-opening.

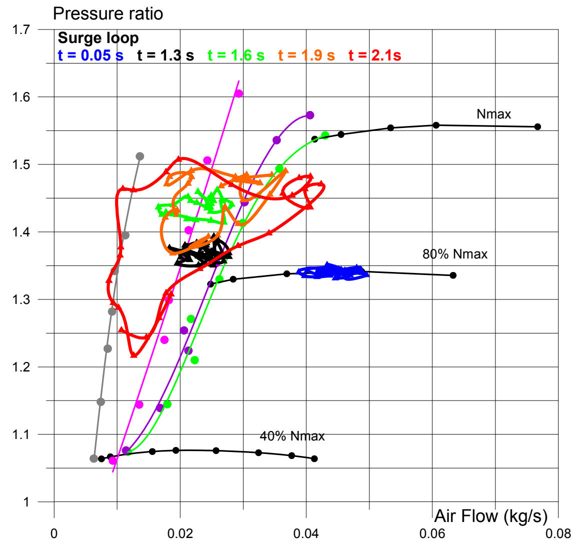

Fig 11. Surge loops evolutions during closing-opening for different initial time.

5 Conclusion

Experiments show that:

• the surge limit appears for lower flow rates when it is determined in transient;
• the surge limit appears for lower flow rates when closing the throttle valve.

These results are very interesting as a larger margin could be expected from turbocharger manufacturer surge line curve in the case of a valve closing at an inlet of the compressor.

Previous experiments showed that closing a valve at inlet of a compressor increases the margin line but this one could be decreased for very important closing [14]. So, additional experiments have to be done to confirming the present behaviour for more important closing.

Also, the complete or almost complete quick closure of the electric throttle valve must be experienced. At present, the pilot valve before the inlet of the turbine can be controlled electrically but it takes a long time. So we can have during these experiments turbocharger overspeed and risk of damage. So, new methods of controlling the turbine speed should be considered for future experiments

Measurement with a hot wire does not give the direction of air flow which could be negative for deep surge. In this case, we have to correct the sign of the air flow. A special procedure has been already applied [8]. At present, we are using an ultrasonic air flow meter. The first results are promising.

Tests are also foreseen to establish the effect of closure at the outlet of the compressor.

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