PAPER • **OPEN ACCESS**

Turbocharger surge behavior for sudden valve closing downstream the compressor and effect of actuating variable nozzle turbine

To cite this article: A Danlos *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **960** 012013

Turbocharger surge behavior for sudden valve closing downstream the compressor and effect of actuating variable nozzle turbine

A Danlos[1*], P Podevin[1], M Deligant[2], A Clenci[3], P Punov[4] and S Guilain[5]
[1]Le Cnam, Arts et Metiers Institute of Technology, LIFSE, HESAM Université, F-75003 Paris, France
[2]Arts et Metiers Institute of Technology, Le Cnam, LIFSE, HESAM Université, F-75013 Paris, France
[3]Department Automobiles and Transport, University of Pitesti, 110040 Pitesti, Romania
[4]Department of Combustion Engines, Automobile Engineering and Transport Université technique de Sofia, Sofia, Bulgaria
[5]Renault SA, Powertrain Advanced Engineering, France

*amelie.danlos@lecnam.net ORCID ID : 0000-0001-7598-7434

Abstract. Surge is an unstable phenomenon appearing when a valve closing reduces the compressor flow rate. This phenomenon is avoided for automotive turbochargers by defining a surge margin during powertrain system design. This surge margin established with measurements in steady state testing regime limits the maximal engine torque at low levels of output. An active control of the compressor could reduce the surge margin and facilitate a transient compressor operation for a short time in surge zone. In this paper, an experimental study of the transient operation of a turbocharger compressor entering the surge zone is performed. Control of the turbocharger speed is sought to avoid unsteady operation using the variable geometry turbine (VGT) nozzle actuator. From a given stable operating point, surge is induced by reducing the opening of a valve located downstream of the compressor air circuit. The effect of reducing the speed of rotation by controlling the VGT valve is investigated, as this should lead to more stable compressor operation. The rotation speed of the turbocharger is controlled to avoid an unstable operating point using servo-actuator of variable geometry turbine. From a stable operating point, the surge appearance is caused by closing a butterfly valve downstream the air circuit of the compressor. The effect on the compressor rotation speed when the opening of variable geometry turbocharger valve is modified is studied. Measurements have been conducted for different control profiles of the VGT valve placed downstream the compressor. This article presents the means used to carry out these tests as well as the results of the measurements of the instantaneous signals of pressure, temperature, flow rate and rotation speed, allowing the analysis of the surge phenomenon.

1. Introduction
Automotive manufacturers use chargers in powertrain systems for reducing CO_2 emissions in internal combustion engines or for increasing performances of proton exchange membrane (PEM) fuel cells as new power of resource [1]. The operating range of compressors in this type of applications is limited by

rotating stall leading to surge. Surge is an instability which appears at low flow rates and high load. The appearance of this phenomenon may cause damages to the turbocharger but also mechanical failures on internal combustion engine if relevant procedures are not applied to avoid it. Surge has been studied for last three decades [2, 3] to design systems to avoid its occurrence [4, 5]. Many parameters affect the surge instability and especially geometry and operating conditions of the compressor but also downstream and upstream geometry circuit [6-10].

Surge limit is determined by stationary experiments on test bench. But on the road, inside the vehicle, this limit can vary because of high altitude [11] or acceleration and deceleration [12]. It is then important to define a criterion to detect the surge limit in use, to adjust and control powertrain for low flow rates. Different methods are suggested in literature: temporal analysis of pressure ratio or mass flow rate, frequency analysis, inlet temperature survey [13-16]. As transient behaviour of compressor is crucial to analyse to prevent surge to appear [17], the detection of surge limit with standard criteria needs adjustments to validate the efficiency of methods [18].

In this paper, an experimental method to control surge in transient operation of turbocharger is proposed, managing variable geometry turbine (VGT) valve during sudden closure of a butterfly valve. Detection of the surge limit in transient case is discussed.

2. Experimental set-up

2.1. Test bench description

Experimental tests have been conducted on LIFSE test bench used to determine turbocharger characteristics [18]. A picture of the test bench is given in Figure 1.

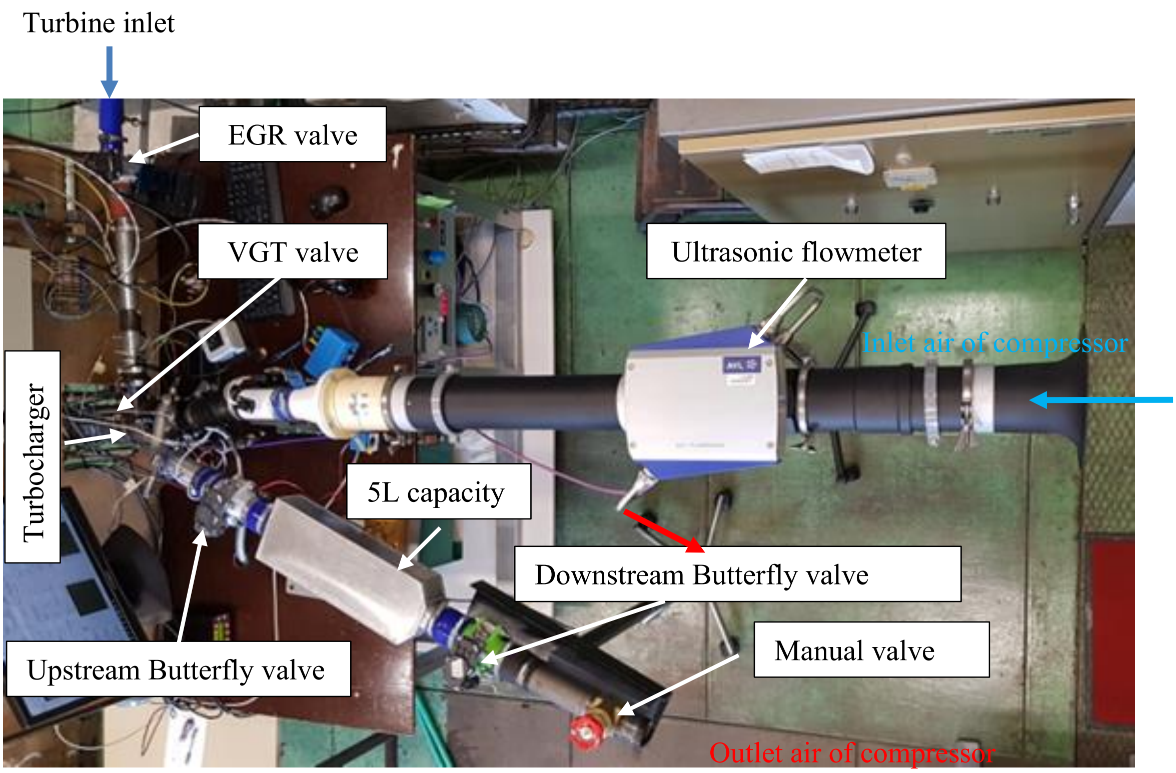

Figure 1. Experimental set-up in LIFSE laboratory.

Turbine is supplied with cold compressed air. Air flow rate is regulated upstream the EGR valve by a pneumatic valve. This EGR valve could be used to vary rapidly the flow rate. Compressed air is exhausted in the test room through a short duct added at the turbine outlet.

An ultrasonic AVL flowmeter is placed upstream the compressor to measure the instantaneous flow rate. An electrically controlled butterfly valve is placed downstream the compressor together with a 5L capacity, another butterfly valve and a manual valve. This manual valve is used to adjust the flow rate in the compressor while butterfly valves are used to modify rapidly the flow rate. The fast modification of flow rate is applied by the valves located downstream or upstream the capacity. The capacity is representative of a charge air cooler. This device amplifies the surge signal while the downstream valve is closed.

Measurements have been conducted on a MHI TDO3L turbocharger. The turbine body and its exhaust manifold are made of cast iron in one entire piece. This one is cut at the manifold position to allow compressed air to be supplied to the turbine.

2.2. Experimental measurements

Piezoresistive sensors are used to measure pressure. Temperature measurements are made with PT 100 ϕ 3 mm 4 wires probes, the flow rate is measured with the AVL FlowSonic flowmeter, the flow rate of the turbine is measured with an orifice plate and a Optel optical sensor measures the speed rotation. These measurements allow to determine the characteristic curves of compressor and turbine in steady state regime.

Measurements of the temperature at compressor rotor inlet and at turbine volute inlet are acquired with K ϕ 3 mm thermocouples associated to a fast converter. Valve positions are given by voltage sensors.

All sensor signals are converted to 0-10 voltage and sent to a National Instruments USB 6218 acquisition card and recorded in an Excel file with a Labview program.

For measurements in steady state, the Labview program shows the operating point and its evolution in the compressor and turbine maps. This operating point is recorded when the stabilization is reached. For each operating point, 1024 data are acquired with a 500 Hz frequency.

For measurements in transient state, another Labview program is applied. Valves control and acquisition measurements use the same acquisition card and the same program. A specific « Producer-Consumer » type loop has been implemented to allow control of valves without impairing the data acquisition. Acquisition frequency is 1kHz and 5120 data are recorded allowing a test duration of 5s for one operating point.

This program permits to keep valves to a constant given position or to describe a "profile". For each valve, the profile is defined according to 6 time steps describing 6 positions.

2.3. Valves control

Valves are actuated by a DC motor supplied with 12V. A sensor supplied with 0-5V determines the valve position. Valves control on engine is made by the ECU (Electronic Control Unit). Valves are supplied by a pulse width modulation (PWM) which is regulated according to the required position.

A UNO R3 Arduino microcontroller which can generate a 5V PWM signal is coupled to a motor module which can control valves with 12 V supply is used. A PID control governed by the microcontroller programing guarantee the closed-loop control position. The difficulty is to find the suitable coefficients to ensure a precise position control, by avoiding overshoot and oscillations and minimizing the response time.

2.3.1. Butterfly valve control

The butterfly valve, Figure 2, has a return spring which keeps the throttle valve open when the power supply shuts down. An example of obtained regulation is presented in Figure 3.

Figure 3 shows a slight difference between the control and the position. For a control fixed to 100%, the position is 97% and for 0%, it is 5%. This difference is inconsequential the valve can be considered completely open at 97% and closed at 5%". Flow rate variations at extreme positions have no significant effect on the flow rate through the valve.

Figure 2. Butterfly valve.

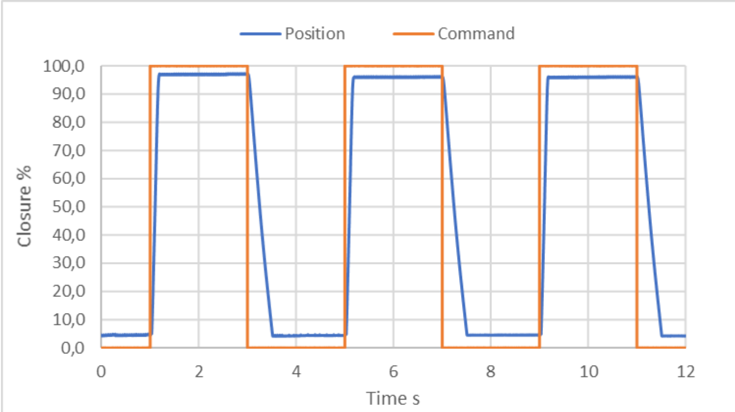

Figure 3. Butterfly valve response to a 0-5V step voltage.

The response time of closing is 0.155 s, of the same order of the response time obtained with the ECU. For opening, the response time is 0.535 s, mainly depending on the return spring as the voltage supply of the valve is shut down. The valve control using a given profile is satisfactory, especially since opening variations for the study are less large.

2.3.2. VGT control

The VGT, Figure 4, actuator has no return spring. So, to inverse the direction of rotation, it is necessary to inverse voltage supply. The response of the valve to a 0-5V step voltage is represented in Figure 5. A very slight difference appears between the control and the valve position. The response time is about 0.2 s for opening and closing operations.

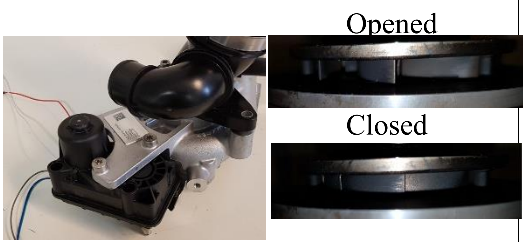

Figure 4. VGT valve.

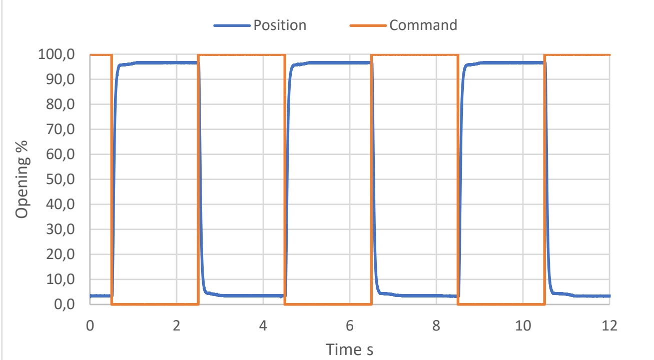

Figure 5. VGT response to a 0-5V step voltage.

3. Experimental measurements

3.1. Surge appearance detection

Extensive tests were carried out for two rotational speed 101,000 rpm and 157,000 rpm. Only the tests with closing the valve downstream of the capacity at 101,000 rpm are presented here. Closure downstream gives high pressure fluctuations. For these tests, the adjustment of the initial operating point is obtained by closing the manual valve. In general, the surge limit is defined by the apparition of a low frequency peak (10-15 Hz) in the fast Fourier transformation (FFT) of the pressure signals while reducing the flow rate with the valve (mild surge). With the considered compressor in this study, this FFT peak does not appear, and deep surge is suddenly reach inducing important vibrations of the capacity. Figure 6 presents the instantaneous values of pressure ratio versus mass flow rate and the temperature measures at the compressor inlet close to the wheel T_{wheel}.

Pressure and flow rate fluctuations appear at point 6. They have the same magnitude for points 7 and 8. The brutal increase of temperature at rotor inlet T_{wheel} indicate the presence of flow recirculation which is also a sign of rotating stall and surge. On this compressor it seems difficult to determine a clear criterion for the definition of the surge limit. This limit has been estimated for a mass flow rate of 0.02 kg/s for 101,000 rpm.

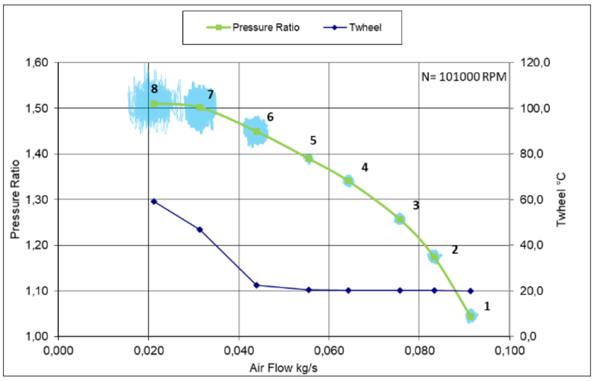

Figure 6. Pressure ratio and inlet temperature vs flow rate
Closure of downstream valve.

3.2. *Transient state experiments*

The experiments consist of positioning close to the surge limit point, using the stationary test program, and then with the transient test program, command the butterfly valve and VGT according to selected profiles. The initial position of VGT is chosen to obtain the minimum power to be supplied by the turbine (maximum efficiency of the turbocharger). Subsequently, only the results obtained for a speed of 101,000 rpm with butterfly valve downstream of the capacity are presented.

The manual valve is significantly closed, three control profiles are applied, Table 1.

Table 1. Butterfly valve closing profile.

Profile 1 (fast closing .2 s)	Time s	0.0	1.0	1,2	1,7	1,9	5.0
	Closing %	70	70	90	90	70	70
Profile 2 (moderate closing time .5 s)	Time s	0.0	1.0	1,5	2.0	2,5	5.0
	Closing %	70	70	90	90	70	70
Profile 3 (slow closing 1.0 s)	Time s	0.0	1.0	2.0	2.5	3,5	5.0
	Closing %	70	70	90	90	70	70

The VGT in its initial position is closed to 70%. A transient test is carried out in this position, Profile 0. A command to close to 90% in 0.2 s is then applied, simultaneously with the closing of the butterfly valve or in phase advance, see Table 2. The profiles have been defined according to a possible engine behavior control.

Table 2. VGT closing profile.

Profile 0 Constant position	Time s	0.0	1.0	1,2	3,2	3,5	5.0
	Closing %	70	70	70	70	70	70
Profile 1 delay 0 s	Time s	0.0	1.0	1,2	3,2	3,5	5.0
	Closing %	70	70	90.0	90.0	70	70
Profile 2 delay 0.2 s	Time s	0.0	0,8	1.0	3.0	3,3	90.0
	Closing %	70	70	90.0	90.0	70	70

Profile 3 delay 0.5 s	Time s	0.0	0.5	0.7	2.7	3.0	5.0
	Closing %	70	70	90.0	90.0	70	70

4. Results

Results for a fast closing of the butterfly downstream valve (Profile 1) and for the VGT Profiles 0 and 3 are presented in Figures 7.1 to 8.4.

Figures 7.1 and 8.1 show the initial position of the butterfly measured at 75% instead of the 70% that were set via the controller. This difference came from the positioning sensor calibration. It does not affect the results of the study and thus it was not considered necessary to apply a new calibration. The control of the VGT is good although there is an instability at 3.5s, which occur outside of the scope of the study.

In Figure 7.2, the increase of the rotational speed and the inlet temperature can be observed as expected due to the closing of the butterfly valve. In Figure 8-2, there is a clear drop in turbocharger speed when the VNT valve is closed and an increase when the butterfly valve is closed. However, the temperature increase occurs only after the butterfly valve closing. On these two graphs, the beginning of surge is indicated based on the temperature increase.

The closing of the VGT reduced the rotational speed and the outlet pressure P2c (Figure 8.3). The pressure fluctuations are less important than when the VNT stay at 70% (Figure 7.3) but they remain significant. The beginning of the surge estimated based on the analysis of P2c signal is the same.

Figure 7.4 and 8.4 show the simultaneous variation of the mass flow rate and the pressure ratio. The instantaneous mass flow rate is negative. The inversion of the flow is clearly a sign of deep surge operation.

Valve downstream the capacity

Profile 0 VGT – Profile 1 Butterfly valve - N = 101,000 rpm

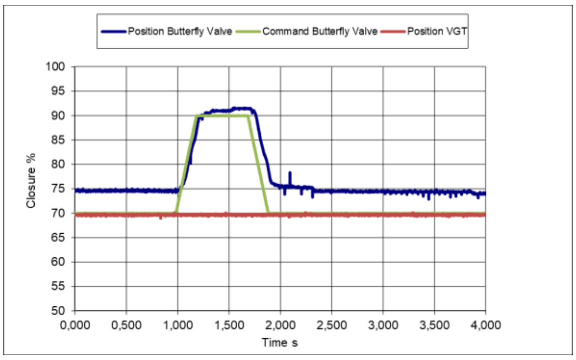

Figure 7-1. Valves control.

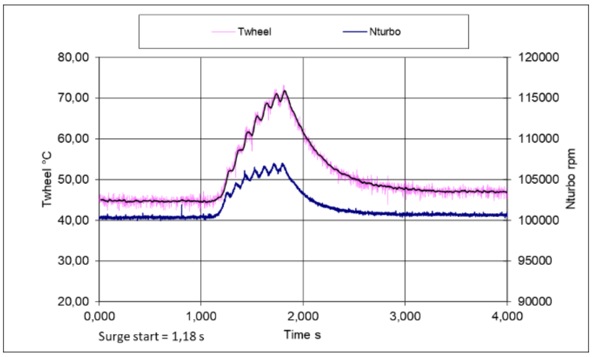

Figure 7-2. Inlet compressor temperature and turbocharger rotation speed.

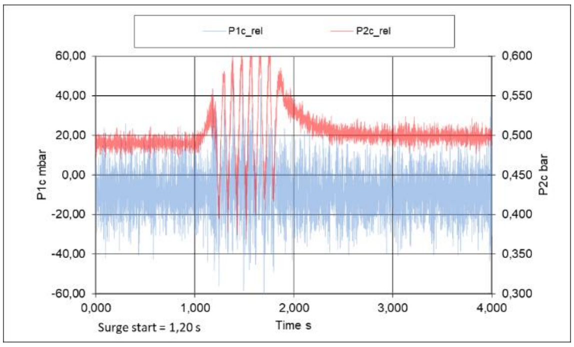

Figure 7-3. Compressor pressure inlet and outlet.

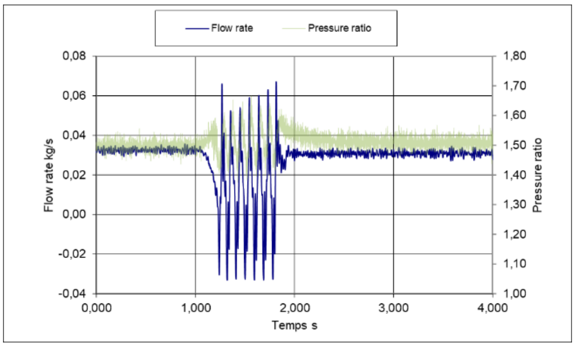

Figure 7-4. Flow rate and pressure ratio.

Valve downstream the capacity
Profile 3 VGT – Profile 1 Butterfly valve - N = 101,000 rpm

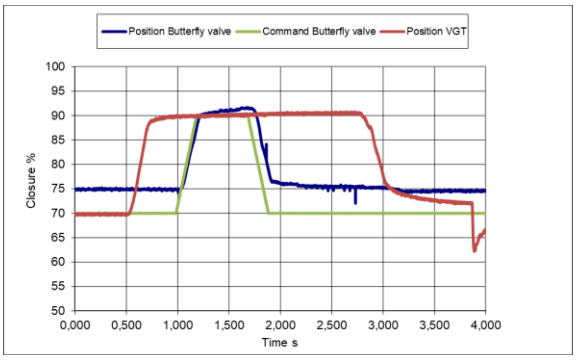

Figure 8-1. Valves control.

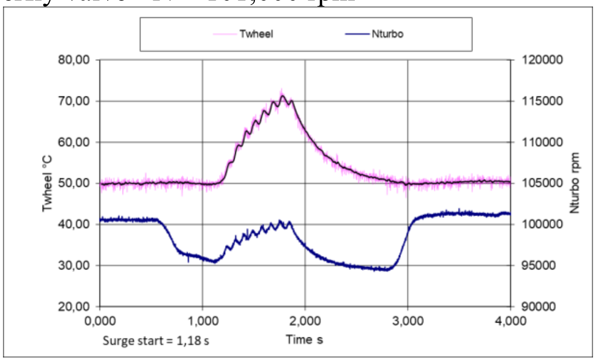

Figure 8-2. Inlet compressor temperature and turbocharger rotation speed.

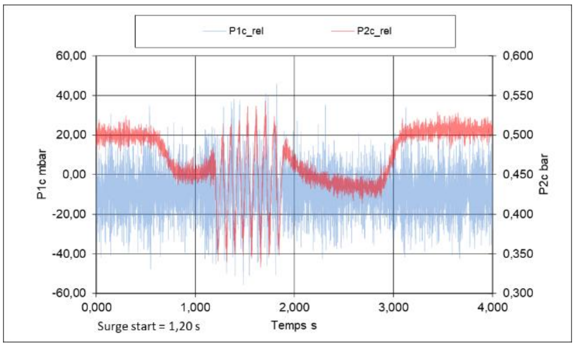

Figure 8-3. Compressor pressure inlet and outlet.

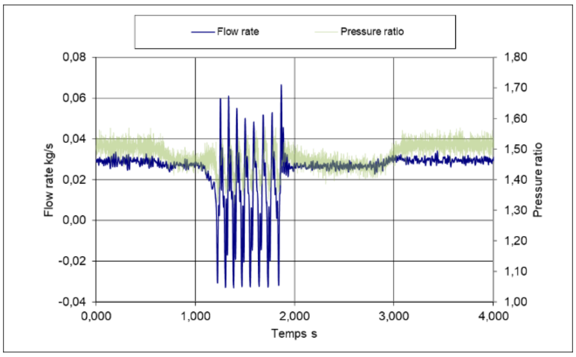

Figure 8-4. Flow rate and pressure ratio.

5. Conclusion

The experiments showed the difficulty to accurately define the surge limit of this particular compressor. The FFT analysis of the pressure and flow rate signals do not allow to observe the progressive apparition of the surge frequency. The surge appears suddenly and with even greater intensity when the butterfly valve is placed after the capacity. The temperature measurement at the rotor inlet highlights the presence of flow recirculation which occurs at flow rate relatively important compared to the surge limit. The analysis of instantaneous values of the pressure ratio versus flow rate shows significant oscillations with amplitudes comparable for stable operation and the surge limit. This makes the determination of the surge limit difficult.

Transient tests demonstrated that the amplitude of the fluctuations is stronger when the butterfly valve is downstream the capacity with significant variations of the rotational speed and the inlet temperature. This does not happen when the butterfly valve is directly placed after the compressor.

The closing speed of the butterfly valve has a logical influence on the beginning of the surge. However, it remains weak and difficult to evaluate precisely due to the impossibility to clearly set the beginning of the surge. Closing the VGT decrease the rotational speed, but it does not seem to have an influence on the beginning of the surge in both case when the VGT closing is synchronized or in advance with the butterfly valve closing. With the rotational speed reduction, the amplitude of the pressure ratio fluctuations decreases but the compressor enters into deep surge anyway according to mass flow rate inversion.

Acknowledgements
We would like to thank Renault for funding this study and providing the material.

References

[1] Dong Kyu Kim, Jeong Hoon Seo, Seonyeob Kim, Min Kyu Lee, Ki Young Nam, Han Ho Song and Min Soo Kim, 2014 Efficiency improvement of a PEMFC system by applying a turbocharger, *Int. J. of Hydrog. Energy* **39** 20139-50

[2] Semlitsch B and Mihaescu M, 2016 Flow phenomena leading to surge in a centrifgual compressor, *Energy* **103** 572.

[3] Day IJ, 2016 Stall, Surge and 75 years of research, J. Turbomach. Trans. *ASME*, **138** 1-16

[4] Mohtar H 2010 Increasing surge margin of turbocharger centrifugal compressor automotive application, *Phd Thesis of Ecole Centrale de Nantes (ECN)*, France.

[5] Danlos A, Podevin P and Toussaint M 2017 Pre-swirl mechanism in front of a centrifugal compressor: effects on surge line and on unsteady phenomena in surge area. *MATEC Web of Conferences* **133**

[6] Greitzer EM, 1976 Surge and rotating stall in axial flow compressors. Part I: Theoretical compression system model, *J. Eng. Power* **98** 190-8

[7] Greitzer EM, 1976 Surge and rotating stall in axial flow compressors. Part II: Experimental results and comparison with theory, *J. Eng. Power* **98** 199-217

[8] Galindo J, Serrano J, Climent H, Tisira A, 2008 Experiments and modelling of surge in small centrifugal compressor for automotive engines, *Exp. Therm. Fluid Sci.* **32**(3) 818-26

[9] Marelli S, Carraro C, Moggia S and Capobianco M. 2016 Effect of circuit geometry on steady flow performance of an automotive turbocharger compressor, *Energy Procedia* **101** 630.

[10] Toussaint M, El Kamel C. 2012 Influence of the Network Geometry on the Surge Characteristics of a Centrifugal Compressor ISROMAC 14, Honolulu, United-States

[11] Wang X, Ge Y, Yu L, Feng X 2013 Effects of altitude on the thermal efficiency of a heavy-duty diesel engine, *Energy* **59** 543

[12] Galindo J, Tiseira A, Navarro R, Tari D, Meano C.M. 2017 Effect of the inlet geometry on performance, surge margin and noise emission of an automotive turbocharger compressor, *Appl. Therm. Eng.* **110** 875

[13] Bontempo R., Cardone M., Manna M and Vorraro G 2017 A statistical approach to the analysis of the surge phenomenon, *Energy* **124** 502.

[14] Andersen J, Lindström F and Westin F 2008 Surge definitions for radial compressors in automotive turbochargers, *SAE Int J Engines* **1** 218.

[15] Liu A.X. and Zheng X.Q. 2013 Methods of surge point judgment for compressor experiments *Exp. Therm. and Fluid Sci.* **51** 204.

[16] Galindo J, Serrano J.R, Guardiola C and Cervello C. 2006 Surge limit definition in a specific test bench for the characterization of automotive turbochargers, *Exp. Therm. And Fluid Sci.* **30** 449.

[17] Rakopoulos CD, Michos CN and Giakoumis EG 2005 Study of the transient behavior of turbocharged Diesel engines including compressor surging using a linearized quasi-steady analysis, *SAE Tech. Pap.*

[18] Deligant M, Danlos A, Podevin P, Clenci A and Guilain S 2017 Surge detection on an automotive turbocharger during transient phases, *IOP Conf. Ser.: Mater. Sci. Eng.* **252** 012082