This is a preprint version of paper:

Galindo, J., Tiseira, A., Arnau, F.J. and Lang, R. (2013), On-Engine Measurement of Turbocharger Surge Limit. Experimental Techniques, 37: 47–54. doi: 10.1111/j.1747-1567.2010.00697.x

This preprint version is not the same than the final version which can be retrieved at publisher's web page

ON-ENGINE MEASUREMENT OF TURBOCHARGER SURGE LIMIT

J. Galindo, A. Tiseira, F.J. Arnau, R. Lang

CMT-Motores Térmicos. Universidad Politécnica de Valencia.

P.O. Box 22012. Spain E46071. galindo@mot.upv.es +34963879656

ABSTRACT

In this paper a new experimental technique is presented to measure the turbocharger surge limit in a regular engine test bench. It is known that the surge margin on engine tests may be very different to that obtained in a steady flow gas-stand. In particular, surge is very dependent on the flow pattern produced by the compressor inlet duct and also on the piping upstream and downstream the compressor. The technique is based in the injection of pressurized air into the intake manifold. In the paper this technique is compared to other ways of measuring the compressor map on engine. Some results with different compressor arrangements are presented and discussed. Finally, this technique allows for measuring not only the actual surge line but also the complete compressor performance map.

INTRODUCTION

Turbocharging is a strategy used for years to increase the internal combustion engine power output. The trend in the last period has been the downsized engine that has similar or even better performance with a lower displacement capacity. Further advantages are obtained with downsizing concerning engine efficiency and pollutant emissions. On the other hand, some drawbacks have to be regarded as well. Since performance is maintained in these downsized engines the maximum air flow is kept almost unchanged. However, to maintain effective torque with lower cylinders displacement, compression ratio in the turbocharger has to be increased proportionally. This is difficult at low engine speed. All this has made the boosting system the key factor in the development of downsized petrol and diesel engines.

The development of automotive engine boosting systems is based on the use of compressor and turbine maps usually supplied by its manufacturer and obtained in tests facilities called gas-stands [1]. In these gas-stands the turbochargers are blown by a steady hot compressed air flow [2][1]. In the compressor side a simple straight duct is usually employed at the compressor inlet, and a big reservoir and a controlling valve at the compressor outlet. The steady compressor map is then obtained closing the valve from an open position progressively until the compressor begins to surge; the turbine flow is set so that the turbocharger speed is kept constant.

Surge phenomenon is known for decades as an instability that appears in centrifugal and axial compressors when they work at low mass flow rate for a given pressure ratio or shaft speed [3]. This results in pressure oscillations that are noisy and can be very destructive in some operating conditions. It is worth to remember that surge is a phenomenon depending not only on the compressor but also on its piping circuit [4]. The surge instability is produced by the coupling between the declining performance of the compressor when air mass flow is reduced and the resistant circuit characteristics [3]. When the compressor flow is reduced from the design point, some stalled flow appears either in the diffuser or in the impeller due to the inadequate design in that operating condition. When the flow is further reduced, these recirculation flows go towards the impeller inlet producing an unstable fluctuating flow that rotates with the wheel movement. This is known as rotating stall [6]. Depending on the compressor speed, this stalled flow can obstruct some of the vanes in the compressor wheel leading to a reduction of the compressor performance in terms of compression ratio and efficiency. This is reflected in a change of the slope of iso-speed lines in the compressor map. The increase of the lines slope combined with the characteristics of the resistant circuit determines the resulting stability operation point [7]. At a given flow rate, the compressor operating point becomes unstable and the compressor begins to surge. Surge leads typically to a low frequency fluctuating flow where the compressor running point goes from the stable operation point to negative flows. This results in pressure oscillations that depending on their amplitude can destroy the compressor quite fast [8].

The problem for automotive engine developer is that the surge line obtained in steady flow bench and with a simple piping around the compressor may differ from the surge limit when the same compressor is tested on the engine test bench [9]. There are several reasons for this different behavior. First, compressor inlet duct is usually different to a straight one. Or it may be modified during the engine development project. Even, there can be different compressor entries for the same engine installed in different vehicles. This can modify impressively the surge limit for better or for worse [10]. Second, the pulsating flow induced by the aspirations of the cylinders has been proved to modify the occurrence of the instability leading to surge. Minimum air mass flow at a given compressor speed may be reduced up to 15% when increasing pressure pulsations amplitude at 200 mbar [11].

The objective of the paper is to propose an experimental procedure to measure the compressor surge limit in actual engine conditions and furthermore using a regular engine test bench. With this method the compressor surge can be characterized with the actual engine conditions concerning the inlet ducting geometry and intake line acoustics. Therefore a more realistic surge limit can be obtained.

Next section presents the description of the facility and the measurement procedure. Then some results are presented to show the benefits of the proposal methodology. Last section states the conclusions of this paper.

DESCRIPTION OF THE EXPERIMENTAL SET-UP

In this work, two facilities are used. The first is a regular gas-stand where the turbocharger compressor map is measured in steady controlled conditions [2]. Figure 1 depicts the gas-stand setup that includes a hot gas steady flow generated in our case by an 11-liter diesel engine. The compressor takes the room air through an air filter and a flow meter, and impels it to a reservoir of about 10 liters and then through a controlled valve the air goes to the atmosphere. Even though this facility has been modified to produce pressure pulses at the turbine and the compressor [11], in this case steady flow in both turbomachines has been imposed.

The second facility used in this work is a regular engine test bench in which the engine speed is controlled with an asynchronous dynamometer. The engine has to be instrumented to measure at least air mass flow and compressor inlet and outlet pressure. Modern automotive engines are usually instrumented with a hot plate anemometer between the air filter and the compressor, and absolute pressure piezorresistive gauges at the filter outlet and at the intercooler outlet. With these sensors it is possible to obtain the performance map of the compressor where some pressure losses in the piping and intercooler are included.

It is not easy to lead an automotive turbocharger mounted on the engine into surge. First, the engine full load is limited among other criteria by surge occurrence. Second, air flow and compression ratio cannot be freely modified since they are linked to the volumetric pump that is the engine. Consequently, when the boosting pressure is increased the mass flow rate increases as well. The only way to make the turbocharger on an engine running properly is during transient tests, e.g. releasing the accelerator pedal suddenly at full load and low engine speed. These tests are not suitable to measure the surge line because it is hard to determine in transient the flow conditions just before entering into surge and then to locate these points on the compressor map.

There are different ways to make independent the compressor and engine flows having their pros and cons. The first is to make a bleeding of the air coming from the turbocharger to the atmosphere so that the compressor air mass flow is different (higher) than that of the engine. The problem is that it is usually impossible to go to surge because the air flow in the compressor is maintained. A second method is to open the intake manifold to the atmosphere. In this procedure a valve is needed downstream the compressor to control the turbocharger compression ratio. For this purpose, the intake throttle in both petrol and diesel engine can be used. The flaw in this technique is that the engine becomes naturally aspirated and the turbine flow and work is reduced. This limits the energy available and only compressor operating points below a given speed can be measured. Besides, with this method the engine is not connected to the compressor and therefore pressure pulsations generated by cylinder aspirations are not accounted for.

The method proposed in this paper is to inject compressed air into the intake manifold so that the engine air flow will be the addition of the injected plus the compressor air flows. Since the air mass aspirated by the engine is depending on the intake manifold density, the more the injected air, the more reduced is the compressor air mass. Compared to the previous method, it has the advantages that the actual intake line is assessed and then the real intake line acoustics is considered. Also, since the air injection system supplies the air the compressor does not, the engine operating point is stable even when the compressor begins to surge. This is important because the turbine is fed steadily and it can blow at very high compressor speeds allowing for measuring the whole compressor map including its surge line. Figure 2 shows a sketch of the system. It includes besides the engine a source of compressed air, the line to the engine and as close to the engine as possible a controlling valve.

The source of compressed air has to fulfill two requirements. The air pressure has to be above the engine boosting pressure and the available flow has to be enough to reduce the compressor flow from full load steady points to surge. The needed flow of pressurized air is related to the distance between the surge line to be measured and the engine full load curve. This can be visualized in the compressor map as the distance between points A and B marked in Figure 3. Hopefully, a simple compressed air supply available in many testing facilities is usually enough to cover these requirements. The compressed air line and the controlling valve have to have an effective section suitable to inject the maximum flow needed. The requirements for the controlling valve besides the maximum section are that the proportionality of the opening section has to be good to control low air flows and it has to be controlled externally to the testing cell. Also, it is recommended that the valve is mounted as close to the intake manifold as possible, but the location where the air is injected into the intake manifold is unimportant. This can be done with a simple manual valve or a controlled one. In current diesel or petrol engines, it is possible to use the EGR valve as controlling valve closing the EGR line in the exhaust manifold. Using the EGR valve has several advantages: first it is usually mounted in the cold side of the EGR valve close to the intake manifold; second, its proportionality is usually very good; and third, it can be controlled changing the air mass flow maps in the ECU (Electronic Control Unit).

The evolution that the compressor will follow when the amount of air injected is increased depends on the control of the turbine.

- If a variable geometry or waste-gated turbine is set to a constant position, the process will be nearly at constant turbine power and the turbocharger speeds up slowly as the compressor mass flow is reduced. This is marked as #1 in Figure 4. To do this is necessary to put manual control in the ECU turbine controller.
- If it is controlled to hold constant boosting pressure the process will be at constant compressor ratio reducing slightly the turbocharger speed. This is the actual control strategy for the turbine in automotive engines, so that it is the natural strategy is the ECU is left as it is (mark #3 in Figure 4).
- If the test cell has the possibility to control externally the turbine or waste-gate position, it may set to maintain constant corrected turbocharger speed so that the usual compressor map at given compressor speed may be obtained (mark #2 in Figure 4).

The testing procedure is as follows. The engine operating point is set to full load and low speed. If possible, it is good to approach to surge closing further the turbine. Care must be taken with maximum in-cylinder pressure limit value. Then, the measurement recording is switched on and the air injection valve is progressively open reducing the air flow through the compressor. This opening process has to be as slow as possible to get an even evolution of flow variables in the moment before going into surge. Surge may be detected in different ways such as noise, temperature increase at the compressor inlet or increase in the oscillations amplitude in air mass flow or inlet or outlet pressure sensors. This can be visualized in an oscilloscope during the tests. The whole transient process is registered with the high and low frequency acquisition systems. To detect surge a sampling rate of 100 Hz is high enough. The type of signals measured is presented in Figure 5. It can be seen that the evolution going from stable to surge operation is smooth and it is clear when the instability develops so that the last stable operating point can be obtained by averaging the dynamic signals just before surge develops. This is marked as red line in Figure 5. This procedure is repeated for different compressor compression ratios or speeds and the whole surge line can be measured.

RESULTS AND DISCUSSION

A first result of the air injection technique as a means to measure the actual on-engine surge line is presented in Figure 6. It is plotted there the compressor map measured in a regular gas-stand with a straight inlet duct. In this map it is represented the full load operating points of a 2.2 liter automotive diesel engine. It is worth to remark that the full load curve goes into the surge zone as predicted by the steady map. The air injection technique allows for measuring on the engine test bench a different surge line with the same compressor entry geometry. This is marked in Figure 6 as green dots. Using the air injection technique it is possible to reach values of compression ratio as high as 3. Most important, air injection technique allows for measuring different compressor inlet geometries. In Figure 6 a bended duct at the compressor inlet surge line is presented (pink squares). This results show how a well designed entry may enlarge surge margin allowing for an increase of engine low end torque.

A second result in a different engine is presented in Figure 7. Several compressor inlet geometries have been tested in a 1.6 liter automotive diesel engine. In this case, surge line measured on the gas-stand with a straight pipe in the compressor inlet (thin continuous line) does not differ to much from that measured on engine with the air injection technique at low speed (thick green line with triangles). But the agreement is worse at high speed. Other compressor inlet geometries have been measured on engine as well. The bended pipe with an elbow at the compressor inlet (thick pink line with dots) does not produce in this particular case much increase in surge margin. Compared to previous engine result it has to be said that the bend radius in this case is larger and then the effect of the elbow is lower. A tapered pipe with an angle of 19º at the compressor inlet (thick blue line with squares) leads to higher surge margin compared to the straight pipe case. Finally, the best among all the geometries tested was a cylindrical plenum of 1 liter volume installed at the compressor entry (thick red line with diamonds).

In Figure 7 it is plotted a dashed line indicating the loci of engine operating points at constant speed. The intersection of the engine line with the different surge lines show the potential increase in compression ratio/mass flow with each compressor inlet geometry. The figure shows that the gas-stand test would predict a compression ratio value of 1.5, while the on-engine tests with the straight and bended pipe should predict 1.6, the tapered pipe 1.7 and finally, the plenum more than 1.9. This clearly shows the importance of a good estimate on surge margin on engine low end torque prediction.

The air injection technique to measure surge line has many advantages. First, surge line is measured in real engine conditions. Pressure pulsations are very similar to those of the engine. It is true that the air injection modifies slightly the acoustics of the entire intake line, but if the controlling valve is located as close as possible to the intake manifold, the change in acoustics would be low. In this way, to use the EGR valve as controlling valve is a good option.

A second advantage of the air injection methodology is that surge points may be measured at relatively high compressions ratios as proven above. Since the engine air intake is maintained during the test, energy release from combustion and turbine work, also are. With other ways to lead the compressor to surge, the reduction in air mass flow is translated in less turbine power and so less compression ratio at a given engine speed can be reached.

A third benefit of the proposed methodology is that the transient process from stable to unstable operation is really smooth in a quasi steady manner as it can be seen in Figure 5. As already mentioned this eases the accurate determination of the surge line. Even once the compressor is in surge all the engine parameters can be maintained because the loss of compressor performance due to surge is compensated by the air injection system. In other methods, once the compressor becomes unstable, the decrease in air mass flow may enter the engine into the smoke limiter control reducing the injected fuel. This makes the engine torque to be reduced. Next, depending on the control of the test bench low frequency cycles may appear where the compressor enters in surge, the engine speed increases, then the compressor becomes stable again, the engine speed decreases and so forth.

CONCLUSIONS

A procedure to measure a compressor map and more precisely its surge limit on the engine test bench has been presented. This technique allows for measuring the surge limit in actual engine conditions accounting for the effect of the compressor inlet geometry and the entire line acoustics. The procedure consists in inject compressed air into the intake manifold reducing progressively the air mass flow through the compressor. This procedure allows to lead the compressor to surge in a very smooth test so that the last stable point can be accurately measured. Depending on the controls in the turbine side slightly different trajectories can be followed on the compressor map.

The air injection technique has been used to measure surge lines with two different engines with different compressor inlet geometries and compared to the surge line measured in a steady gas-stand. The results show that the proposed methodology leads to more realistic results in terms of surge margin and allows for comparing different geometries.

The proposed technique has several benefits. It accounts for actual engine conditions including the effect of the compressor entry geometry and engine intake line acoustics. Second, the complete compressor surge line can be measured up to high speed. And finally, the tests is carried out in transient but it is a sequence of quasi-static conditions and the compressor goes into surge in a smooth manner.

ACKNOWLEDGMENTS

This work has been funded by Spain's Ministerio de Ciencia y Tecnología through project TRA2007-65433. The authors acknowledge R. Luján for his valuable contribution to the tests. Ricardo Lang is indebted to the Generalidad Valenciana through grant GRISOLIA/2008/009.

REFERENCES

[1] Hajilouy-Benisi, A., Rad, M. and Shahhosseini, M.R., "Empirical assessment of the performance characteristics in turbocharger turbine and compressor", *Experimental Techniques*, **34**: 54-67 (2010). doi:10.1111/j.1747-1567.2009.00542.x

[2] Galindo, J., Serrano, J.R., Guardiola, C. and Cervelló, C., "Surge limit definition in a specific test bench for the characterization of automotive turbochargers", *Experimental Thermal and Fluid Science*, **30**: 449-462 (2006).

[3] Oakes, W.C., Lawless, P.B., Fagan, J.R. and Fleeter, S., "High-speed centrifugal compressor surge initiation characterization", *Journal of Propulsion and Power*, **18**: 1012-1018 (2002).

[4] Galindo, J., Serrano, J.R., Climent, H. and Tiseira, A., "Experiments and modelling of surge in small centrifugal compressor for automotive engines", *Experimental Thermal and Fluid Science*, **32:** 818-826 (2008).

[5] Fink, D.A., Cumpsty, N.A. and Greitzer, E.M., "Surge dynamics in a free-spool centrifugal compressor system", *Journal of Turbomachinery*, **114**: 321-332 (1992).

[6] Greitzer, E.M., "Surge and rotating stall in axial flow compressors - 2. Experimental results and comparison with theory", *J Eng Power Trans ASME*, **98A**: 199-217 (1976).

[7] Gravdahl, J.T. and Egeland, O., "Centrifugal compressor surge and speed control", *IEEE Transactions on Control Systems Technology*, **7**: 567-579 (1999).

[8] Kurz, R. and White, R.C., "Surge avoidance in gas compression systems", *Journal of Turbomachinery*, **126**: 501-506 (2004).

[9] Engeda, A., Kim, Y., Aungier, R. and Direnzi, G., "The Inlet Flow Structure of a Centrifugal Compressor Stage and Its Influence on the Compressor Performance", *Journal of Fluids Engineering, Transactions of the ASME*, **125**: 779-785 (2003).

[10] Galindo, J., Serrano, J.R., Margot, X., Tiseira, A., Schorn, N. and Kindl, H., "Potential of flow pre-whirl at the compressor inlet of automotive engine turbochargers to enlarge surge margin and overcome packaging limitations", *International Journal of Heat and Fluid Flow*, **28**: 374-387 (2007).

[11] Galindo, J., Climent, H., Guardiola, C. and Tiseira, A., "On the effect of pulsating flow on surge margin of small centrifugal compressors for automotive engines", *Experimental Thermal and Fluid Science*, **33**: 1163-1171 (2009).

[12] Payri, F., Galindo, J., Climent, H. and Guardiola, C., "Measurement of the oil consumption of an automotive turbocharger", *Experimental Techniques*, **29**: 25-27 (2005).

LIST OF FIGURE CAPTIONS

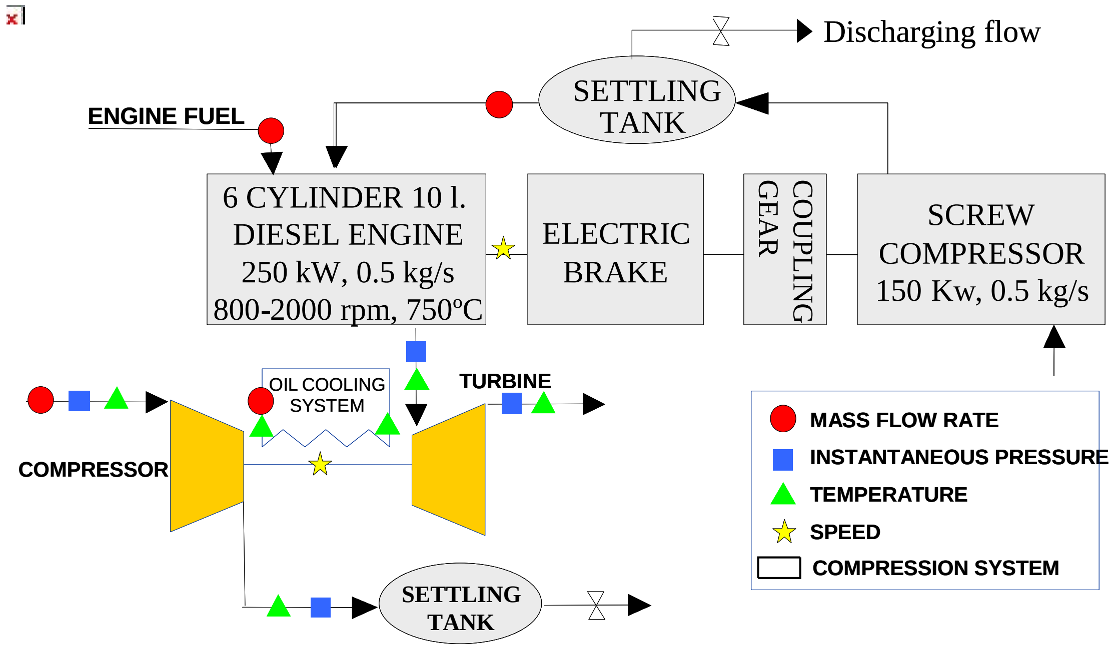

Figure 1. Layout of the gas-stand.

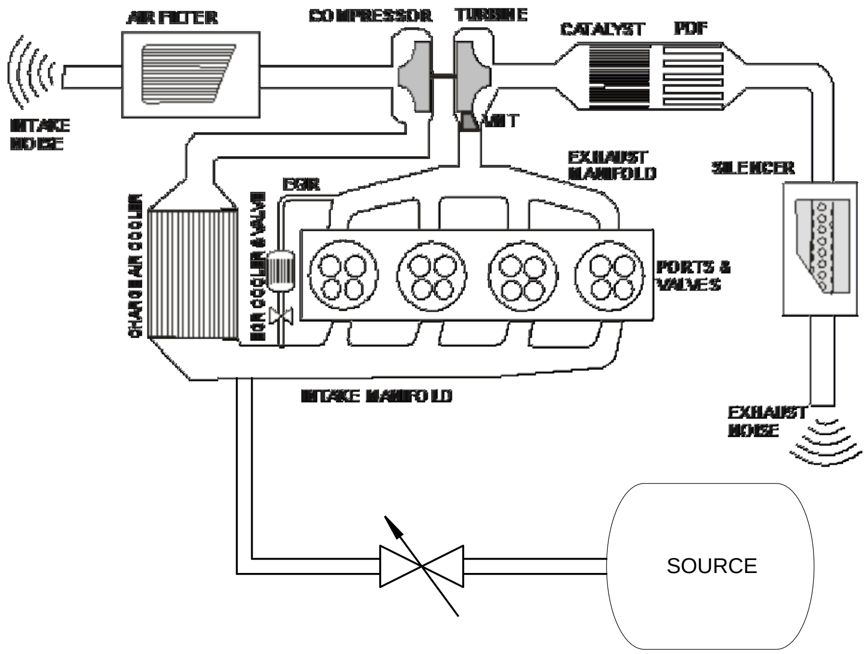

Figure 2: Engine layout with the air injection system.

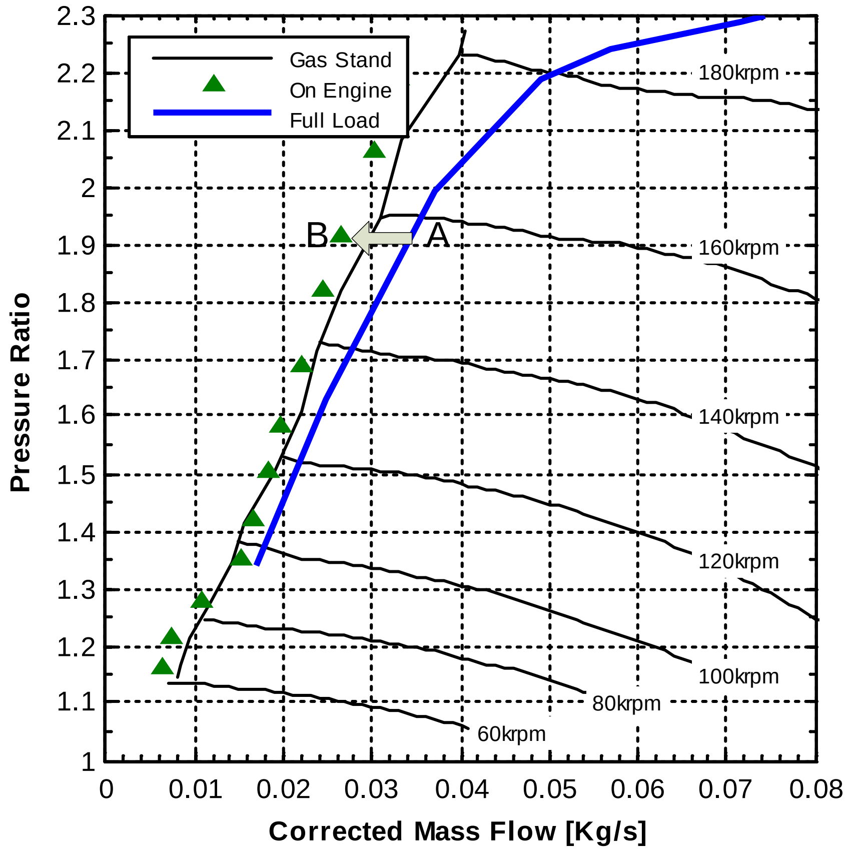

Figure 3. Compressor map measured on a regular gas-stand, engine full load and surge limit points (triangles) measured by air injection technique.

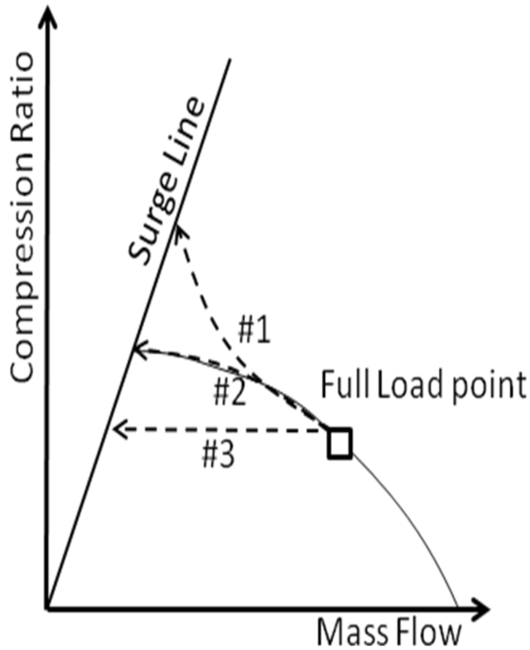

Figure 4. Trajectories of different air injection tests with different turbine control strategies.

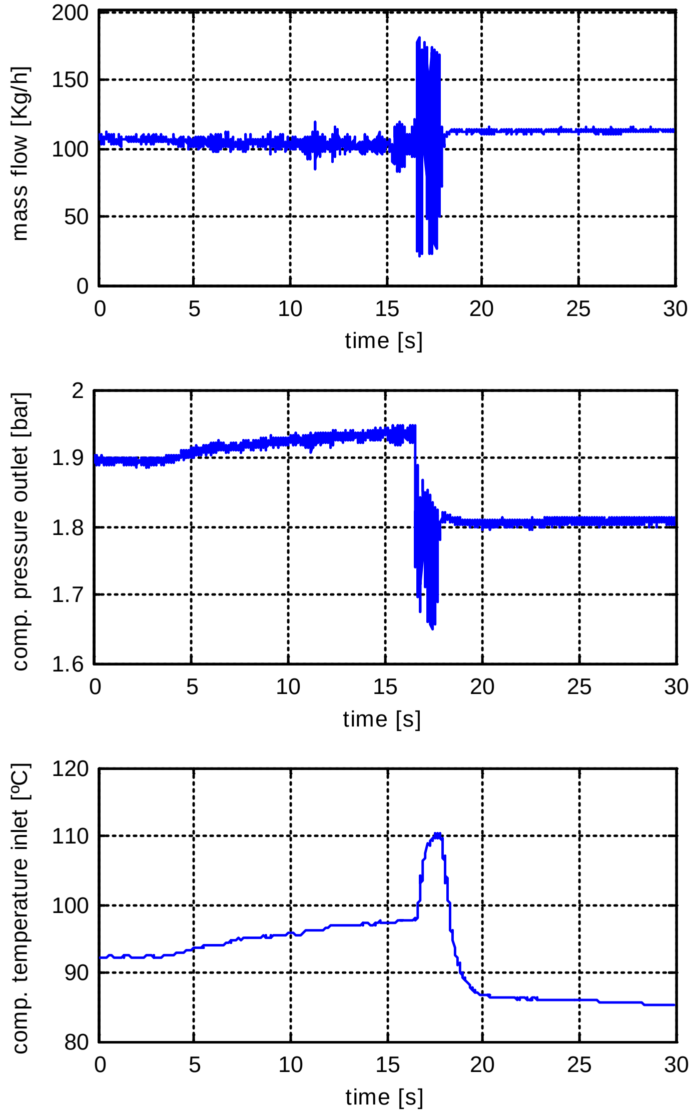

Figure 5. Evolution of some measured signals during the air injection test.

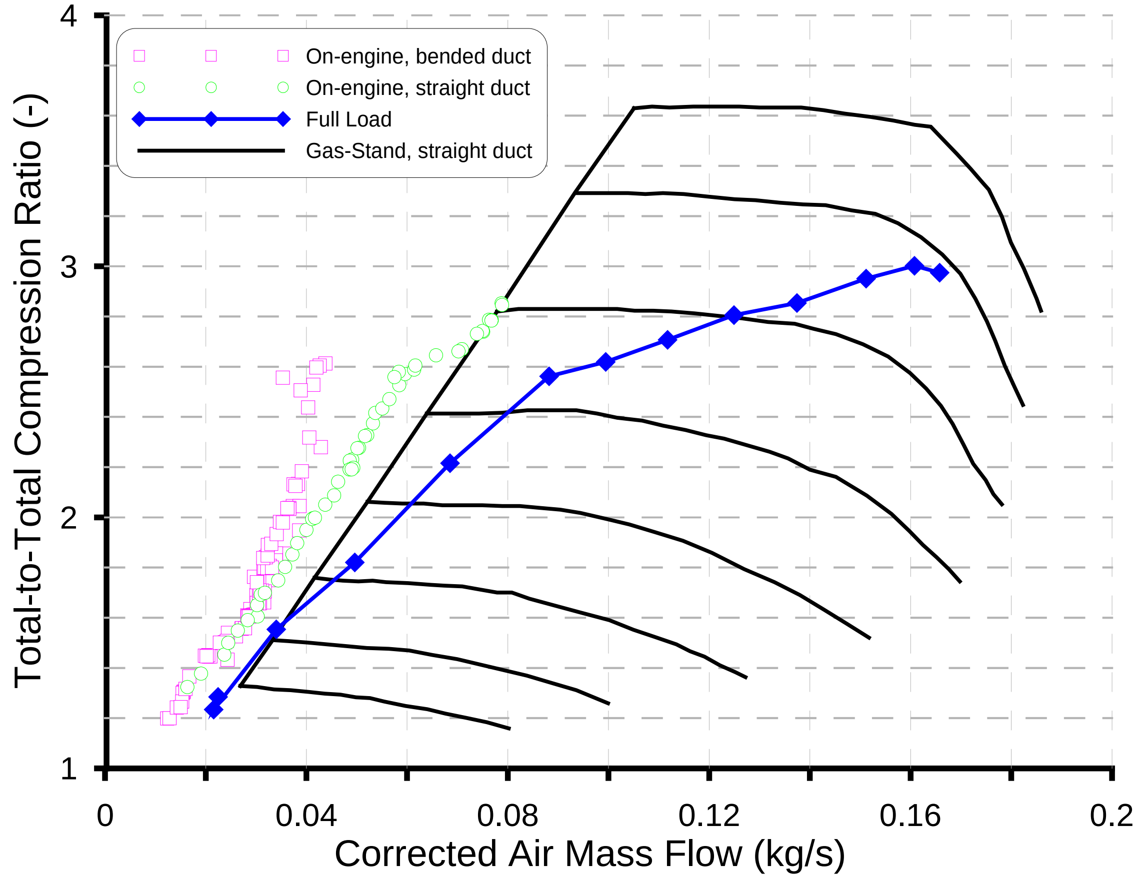

Figure 6. Compressor map with gas-stand surge line (continuous black line), on-engine with a straight pipe (green dots), on-engine with a bended pipe (pink squares).

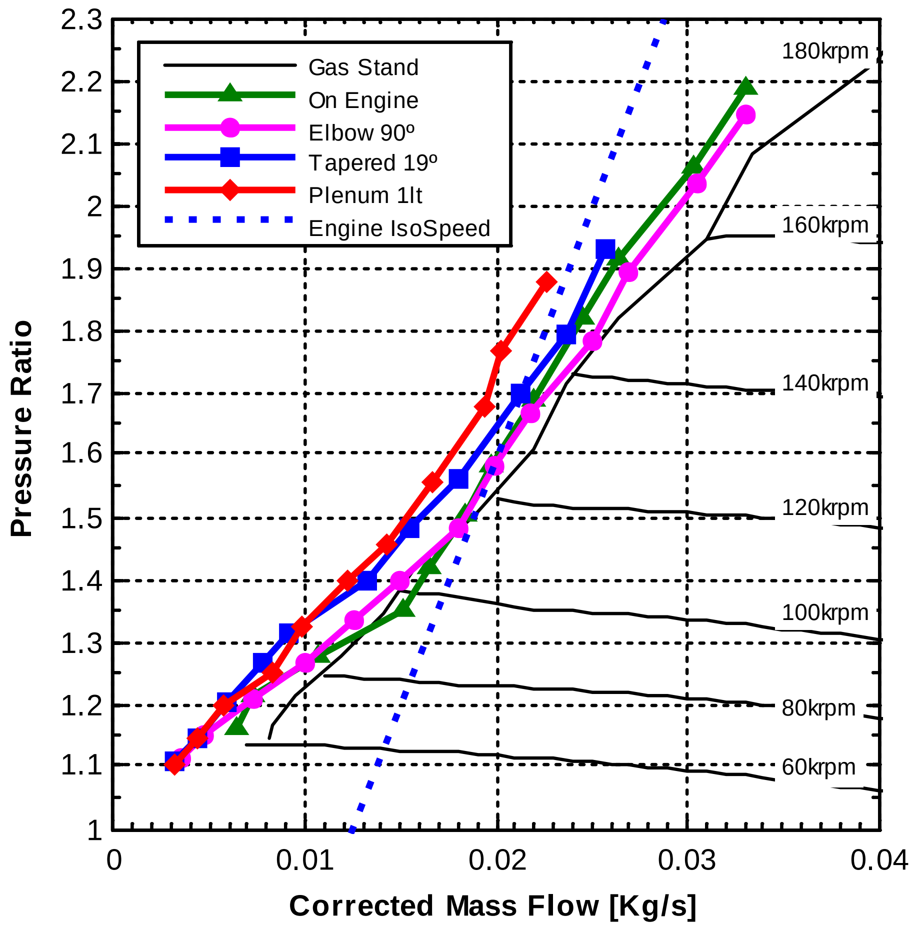

Figure 7. Surge lines measured with air injection technique corresponding to different compressor entry geometries.