1) Introduction

During the use of centrifugal compressor for turbocharging diesel engines, the compressor is connected to one circuit, more or less complex including capacities and lengths pipes (air filter, RAS : supercharger air cooler, bends, resonator…) These different network geometries have a very high influence on the « surge line » position (see figure 1), as well as on the surge loop (figure 2).

![Figure 1](image1.png)

This surge loop area (pressure ratio vs mass flow-rate fluctuations) represents the unsteady pressure fluctuations and mass flow fluctuations affecting the centrifugal compressor and the diesel engine.

In this paper, we propose an analysis of surge characteristics of a centrifugal compressor, and more particularly the evolution of its « surge loop » which characterizes the intensity of the unsteady pressure fluctuations (very dangerous for the compressor) and mass flow-rate fluctuations (disturbing and possibly dangerous for the engine).

![Figure 2](image2.png)
2) Surge phenomenon of a Centrifugal compressor.

Turbomachinery compressors operating at very low flow-rate are disturbed by the occurrence of aerodynamic flow instabilities: rotating stall and surge. These instabilities of the internal flow in the compressor are also reflected by vibrations and an intense noise but also by the compressor temperature which never stabilizes. These instabilities are observed at frequencies of some tens of hertz.

Attempts (desired or not) to operate under this regime quickly lead to the compressor damage and its associated circuit. During this prohibited regime because it’s dangerous, the operating point describes a loop more or less spread which characterizes the intensity of this phenomenon called “compressor surge”. On the figure 2, we show the experimental surge loop raised in of a centrifugal compressor operating on its surge area in pumping for a rotational speed of 100 000 rpm. The surge intensity can be characterized by the amplitude of the fluctuations of the compression ratio associated to the frequency of these fluctuations. The stresses in the compressor blades vary as the pressure fluctuations. Fatigue imposed on the blades is more intense if these fluctuations occur at high frequency. If we wish to represent the surge intensity by the surface of the surge loop, the analysis is then the following one:

- At iso-surface of the loop, a loop elongated in the direction of the compression ratio fluctuations will be more harmful to the compressor than a loop elongated in the direction of the mass flow fluctuations.

- From one point of view of the compressor, it is the fluctuations of pressure with high frequency that are harmful to its integrity. For journal and thrust bearings, the fluctuations of the mass flow and its frequency are undoubtedly more important than the only fluctuations in pressure.

- In the case of a turbo-charging internal combustion engine, it’s certain that the mass flow fluctuations with high frequency due to the compressor surge will most affect the engine. Indeed, the turbocharged air pressure fluctuations due to surge will be diminished and drowned by the compression in the engine cylinder.

3) Definition of the surge compressor intensity.

When the compressor works into its surge area, the operating point don’t stay a “stable” point but describes a surge loop as seen in the figure 3.

Surge intensity may be characterized by the importance of the pressure ratio fluctuations associated to its frequency. (figure 4)

The stresses in the compressor blades vary as the pressure fluctuations. Fatigue imposed on the blades is more "intense" if these fluctuations occur at high frequency.
4) The experimental study.

Many experiments were realized for two years. The results which we present here concern:

- The influence of the geometry of the upstream and downstream circuits on the “surge loop”.

Geometrical configurations tested for both upstream and downstream circuit are the subject of figure 5. Three volumes of capacity respectively 2, 5 and 20 liters and three ducts’s lengths of 440, 700 and 1000 mm allowed varying the upstream and downstream geometries.

4.1) Study of the surge loop.

The surface swept by the «surge loop» represents the intensity or the energy of dissipation during surge. The figures 6, 7, 8 and 9 summarize the evolution of these loops according to the different geometries tested. Each figure presents the loop’s shape for three rotational speeds of the compressor: 60 000, 80 000 and 100 000 rpm.

Figure 6. Upstream volumes 2, 5, 20 dm$^3$.

The figure 6 shows the little influence of the volume at the upstream of the compressor on its behavior during surge. A value close to 5 liters seems optimal to minimize the effects of the surge that result primarily from pressure ratio fluctuations. The upstream volume reduces the
mass flow fluctuations but against it increases the fluctuations frequency (see paragraph 4.3)

The figure 7 shows a much greater influence of a volume disposed in the compressor discharge. The loops “surface” (hence the surge intensity) is important for the volume of 2 liters compared to 5 and 20 liters. The "energy buffer" that is, this volume, thus reducing fluctuations of the flow-rate and of the pressure. The instabilities frequency is almost divided by 2 by the presence of this volume downstream the compressor. (sea paragraph 4.3).

The figure 8 also shows a less important influence of the upstream duct’s length on the pressure fluctuations. On the other hand, the mass flow fluctuations increase with this duct’s length. The loop described by the operating point presents one or two nodes according to the duct’s length. These features found on the surge loop are so far not clearly explained. The position of the mass flow measurement from the compressor inlet can affect the loop’s shape.
Figure 9. Downstream ducts’s length: 440, 700, 1000 mm

The figure 9 shows a downstream duct's length effect which appears especially on the pressure fluctuations. The increase of the downstream duct’s length reduces the instabilities frequency. The amplitude of the pressure fluctuations observed here could be compared with those induced by the effect of the volume (Figure 7). The increase in length corresponds also to an increase in volume could explain the similitude between the two geometries.

4.2) The surge loop evolution.

In figure 10, we can see the evolution of the surge loop for an uniform operating point in surge (at 100 000 rpm rotational speed) depending on the geometry of its associated circuit.

Figure 10. Surge loop - vs - geometrical configuration.
The figure 10 summarizes the influence of the different geometries upstream-downstream on the “intensity” (represented for example by the surge loop area) of the surge phenomenon for the same operating point at 100000 rpm. The pressure ratio fluctuations are almost identical regardless of the upstream or downstream geometry. This pressure ratio in an established surge fluctuates between 1.6 -1.7 and 2 for this value of rotational speed. The mass flow variations are against more sensitive to the geometry and are maximal with an important upstream duct’s length. The volume effects are more influential when the volume is placed downstream of the compressor circuit.

4.3) Frequencies evolution vs geometrical configurations.

The figure 11 presents the variations of the surge frequencies with the geometrical configurations at the rotational speed of 100 000 rpm.

- The upstream volume is the most damaging device because it greatly increases the instabilities frequencies and therefore the stress and fatigue of the compressor.

- In contrast, the presence of a volume downstream the compressor calms these instabilities, which is obviously desirable for the compressor and its network.

5) Remarks.

5.1) On the gas-stand compressor test-bench (figure 12). In the beginning of 2003, first experiments showed the ability of our test-bench to measure instantaneous compression ratio, temperatures variations and instantaneous flow-rate in the surge area of a centrifugal compressor. It is possible to work in such conditions for the compressor at relative low rotational speed (maxi 110000 rpm) during few dozens of seconds while preserving the integrity of the compressor and its associated system. This experimental time is sufficient to record experimental data. (Labwiev acquisition’s card at 1000 Hz).

5.2) On the detection of surge apparition. It is known that the compressor operating closed to surge area is featured by slight fluctuations of pressure and mass flow-rate. Anyone criterion or method to detect the surge apparition are satisfying. The rotational speed of the compressor is regulated by the action on the turbine admission valve. Simultaneously, the downstream valve of the
compressor is gradually shut-off to reduce the mass flow-rate, until getting closer to the surge area. In order to determine the surge limit for each geometrical configuration, we are watching in real time (on the computer cren) to the operating point (instantaneous pressure ratio / vs / mass flow-rate). The surge limit is reached just before the apparition of a surge loop in substitution to the operating “point” (see figure 2). This phenomena is in agreement with the characteristic noise emitted by the compressor (the frequency and the level of noise are highly altered). My conviction is that the more satisfaying detection method is the reunion of these two events.

5.3) On the compressor’s integrity. Stresses on rotor’s blade are in first due to the pressure fluctuations. Strain of the blades is more intensive for higher frequency of surge phenomena. Consequently, the better geometrical configuration, for the compressor’s integrity will be obtained with an important volume disposed at the downstream part of the circuit in association with a moderated length of pipe.

6) Conclusions.

The first conclusions to be drawn from these experimentations are difficult.

5.1) What can be said that, contrary to assumptions formulated in the Greitzer model [1], [2], [3] the upstream circuit of the compressor has a great importance and should be considered in the surge analysis and also influences the instabilities seen during the surge phenomena.

5.2) In order to deepen the upstream duct’s length effect on the surge loop shape, additional experiments are strictly essential.

5.3) When using centrifugal compressor in turbo-charging internal combustion engines, the motorist will bring special attention to the downstream circuit (the RAS: air cooler volume and the duct’s lengths for an engine connection). Note, however, the beneficial influence of this downstream volume, which strongly reduces the frequency and therefore the stresses to the fatigue of compression facilities.

5.4) The aerodynamic aspect of the associated compressor’s circuits that wasn’t mentioned for the moment, should also be the subject of experimentations and represents the next step in this research on the surge compressor behavior.

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Bibliography.


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