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Surge detection on an automotive turbocharger during transient phases

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Abstract. The surge limit on automotive turbocharger needs to be avoided to prevent operations with pressure and mass flow oscillations. Mild surge is accompanied by noise which is disturbing. Deep surge can cause significant loss of engine power and severe drivability issues. It is necessary to know the stationary limit in order to match a turbocharger with an engine, ensuring enough surge margin. However, this choice does not guarantee surge free operation during transient functioning. In this paper, the surge onset of a compressor while closing a downstream valve is studied. Various tests have been carried out varying the closing time, the position of the initial operating point and the volume of the circuit. The inlet and outlet signals of physical parameters are analyzed with spectral and temporal methods in order to define the instant of the surge occurrence.

1. Introduction

Turbochargers are usually used to increase the specific performances of internal combustion engines, which in the last years was used mainly to replace relatively large naturally aspirated engines with smaller ones without sacrificing the peak performance. This combination of downsizing and uploading an engine is known since long time, but the conversion in an acceptable way of this potential to practice is very challenging. Actually, for a low mass flow rate combined with a high load, the turbochargers may be submitted to instabilities. These instabilities can induce mechanical failures of the turbocharger components and affect engine functioning. As turbochargers manufacturers give only the characteristics measured in steady state operation, to prevent all problems in a vehicle, it is necessary to understand phenomena responsible for the oscillating flow inside the turbocharger, which is called surge. This surge appearance is studied since last three decades [1-4].

The surge phenomenon can also appear for high altitude operation [5] or for acceleration and deceleration [6]. 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 [7-9]. Many authors have discussed different temporal or spectral methods to obtain a criterion allowing to detect the surge appearance on a compressor map. Classical method uses the detection of surge noise, which is a non-sufficient criterion because of the arbitrary feeling of the operator [10]. Sinusoidal signals of pressure ratio or mass flow rate characterize the deep surge and may be a better criterion to identify the surge limit [11,12]. Other methods as the analysis of the standard deviation of temperature signals [13] or frequency domain

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analysis [14,15] have also been applied on automotive turbocharger performance study. The criterion to determine the surge limit is crucial because it has been observed that the turbocharger changes its operating range when the upstream or downstream circuit is different [6,10,16,17]. This implies that manufacturers' compressor map given from a test bench is changed when the turbocharger is placed inside the vehicle.

The study presented in this paper deals with the appearance of surge phenomenon for transient operating conditions of an automotive turbocharger. The criterion for detecting the surge limit is discussed and compared with other methods in order to observe which physical variable is interesting to detect this limit.

2. Experimental set-up

2.1. Test bench description

In our laboratory, we use dry compressed air to set up the characteristic curves of turbocharger. An advantage is to do experiments close to adiabatic conditions which allows to calculate the power demand of compressor easily by applying first law of thermodynamic. The adiabatic hypothesis is not applicable in some case (ex: low speed). Previous works have been presented on this subject [18,19]. Nevertheless, accuracy is always higher than experiments conduct on hot test bench.

A scheme of the test bench is given in Figure 1. The turbine is fed with dry compressed cold air and a valve is used to adjust the speed of the turbocharger to the requirement. Another valve on the compressor downstream of the circuit is used to adjust the resistance of the circuit. By acting on these two valves, an iso-speed can be relatively easily achieved.

An additional ¼ ball valve is used for surge experiments.

The center housing is fed by the lubricating unit with SAE 5-30W oil. Oil temperature and pressure are adjustable respectively from 20 to 120 °C and from 0.5 to 4 bar.

Following measurements are done:

- Compressor and turbine upstream-downstream pressure: with strain gauge transducers
- Compressor and turbine upstream-downstream temperature: usual platinum resistance thermometers have been replaced by K thermocouple of 0.5mm for transient experiments
- Rotational Speed: detection of the influence of metal on inductance parameters
- Compressor air flow: thermal mass flow meter
- Turbine air flow: thermal mass flow meter

For transient experiments, a Constant Temperature Anemometry (CTA) system is linked to a hot film in order to measure instantaneous air-flow and a 0.5 K thermocouple in front of compressor wheel has been added.

All the sensor signals are converted to 0-10 voltage and sent to a USB data acquisition device. The device is controlled by Labview software. For surge measurements, 5120 measurements were done at a scanning speed of 1024 Hz, which corresponds to 5s duration. Data are stored in a file for further processing.

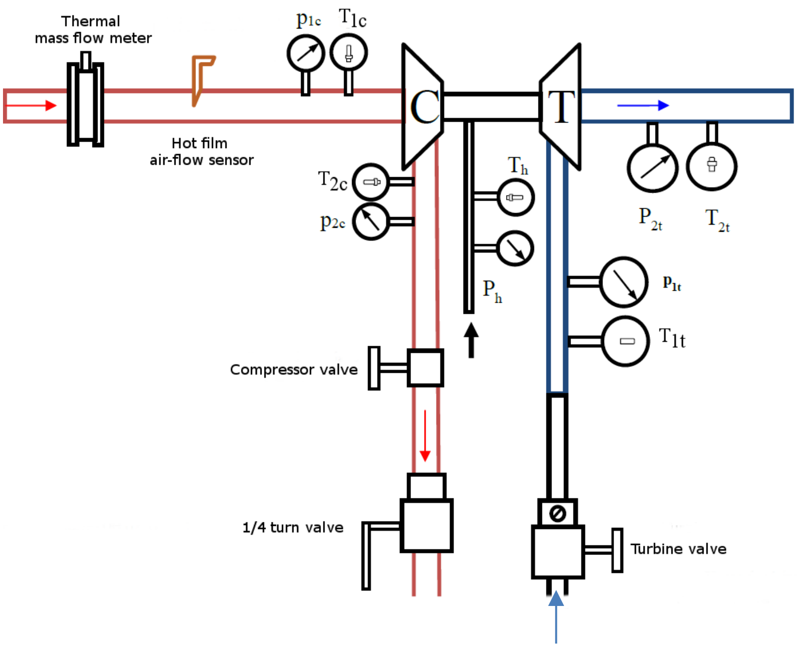

Figure 1: Experimental setup

2.2. Experimentations

This study consists in analysing the transient behaviour of the compressor while entering into surge due to a sudden closing of the downstream valve. Future experiments are planned to simulate surge behaviour on an automotive engine. The turbocharger is Honeywell-Garrett GT15 model equipped with a variable nozzle turbine (VNT). The control device of the guide vanes is set at a position chosen by the operator, in order to allow a quick acceleration of the turbocharger. The position of the turbine valve is adjusted to reach the chosen rotational speed, typically 150,000 rpm.

The initial compressor operating point is defined by the position of the valve at the compressor outlet. When the operating point is stabilized, the ¼ turn valve is manually suddenly closed (a mechanical stop is used to adjust the valve end position). Then the valve is reopened to avoid continued surge operation. The circuit downstream of the compressor is cylindrical with a diameter of 50 mm and a length of about 1 m up to the quick closing valve. In order to test the effect of a modification of the upstream or downstream circuit, a capacity of 0.5 litre can be inserted between the outlet of the compressor and the control valve. This makes it possible to increase the surge intensity and to decrease the resonance frequency. For each test, the acquisition of the data is started approximately one second before valve closing.

In this paper, results of 4 tests with initial rotational speed of 150,000 rpm are presented:

- Test 1: No capacity, initial operating point far from the surge limit
- Test 2: No capacity, initial operating point close to the surge limit
- Test 3: 0.5L capacity, initial operating point far from the surge limit
- Test 4: 0.5L capacity, initial operating point close to the surge limit

2.3. Signal processing

As there is no trigger to start recording the data, the beginning of the records is defined *a posteriori*. The instant of the beginning of the acceleration is defined by analysing the signal of the mass flow rate. Starting from a stabilized operating point, the beginning of the acceleration can be identified as the beginning of the mass flow rate decrease. For example, with the first experiment, the analysis of the signal in Figure 2 shows the beginning of the acceleration at t=1.5s. In order to easily compare the results of different experiments, the beginning of all records is modified to be at 0.5s before the acceleration.

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The mass flow rate is measured using a hot film sensor which is very sensitive and has small response time. A correlation has been experimentally set between velocity measured by the hot film sensor and mass flow measured by the thermal mass flow meter. In case of deep surge, reverse flow can occur. The hot film sensor is not able to provide the direction of the flow. In this study, this problem is solved using the information provided by the inlet pressure sensor which sign is the opposite of the flow rate. So, the sign of the inlet pressure is extracted and used to correct the sign of the hot film sensor measurements. The obtained signal is then filtered with a low pass filter with a cut-off frequency of 100 Hz (see Figure 3).

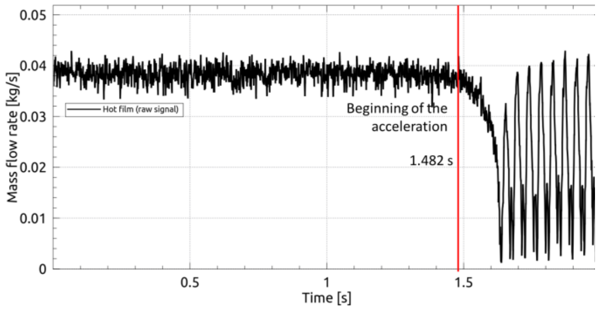

Figure 2: Mass flow rate versus original time

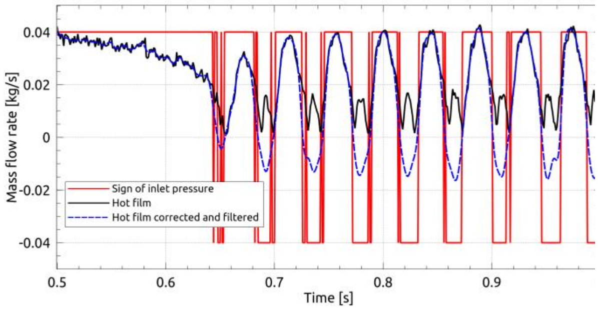

Figure 3: Processing of the hot film signal to get instantaneous mass flow rate

3. Results and discussion

Figure 4 and Figure 5 show the evolution of rotational speed. All tests start at the same rotational speed of 150,000 rpm. Test 1 and test 3 with a mass flow far from the surge line need more power than test 2 and test 4. When the downstream valve is closed, the rotational speed increases due to the reduction of the compressor power while the turbine inlet pressure remains constant. The higher the initial turbine power, the greater the acceleration of rotational speed.

It can also be noticed that the transition to surge appears at the same time (about 0.6s) whether the initial operating point is far or close to the surge limit.

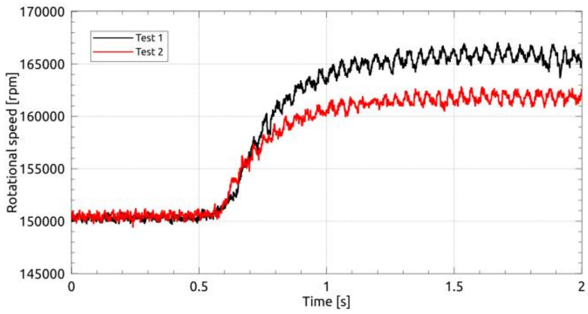

Figure 4: Rotational speed versus time (tests 1 and 2)

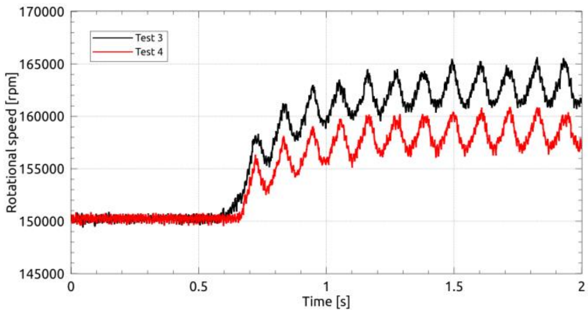

Figure 5: Rotational speed versus time (tests 3 and 4)

Figure 6, Figure 8 and Figure 10 present the temporal signal of pressures, mass flow and temperatures for test 1. On the pressure signals, it can clearly be seen that the pressures increase between 0.5s to 0.7s. Then, both inlet pressure and outlet pressure seem to stall before they start oscillating. The same behaviour can be observed on the mass flow rate signal. This is also confirmed by the observation of the temperature on front of the wheel, which starts increasing. This indicates the presence of flow reversing in front of the wheel which warm up the air at the inlet of the compressor.

Figure 7, Figure 9 and Figure 11 show similar results for test 3. The reduction of the frequency of the oscillation can be easily noticed by comparison with result of test 1. Fluctuations also appear on the temperature measurement.

For all tests, the temperature in front of the compressor wheel has a short response time. It increases quickly after the pressures stall. Using the ratio of the inlet temperature and the temperature in front of the wheel could help predicting the surge limit.

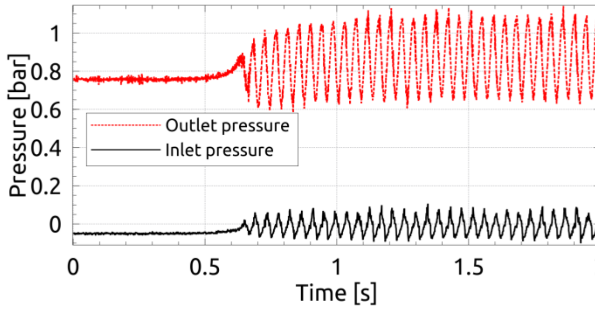

Figure 6: Pressures versus time (test 1)

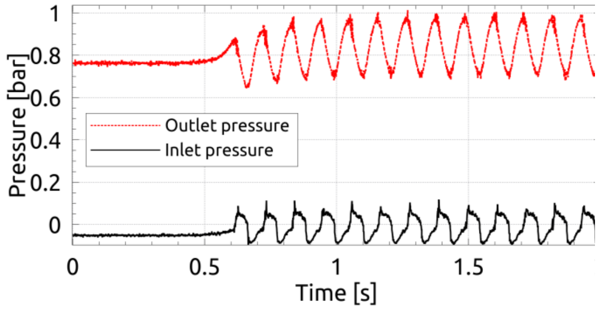

Figure 7: Pressures versus time (test 3)

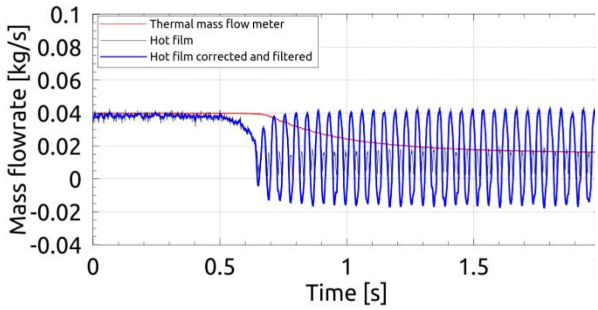

Figure 8: Mass flow rates versus time (test 1)

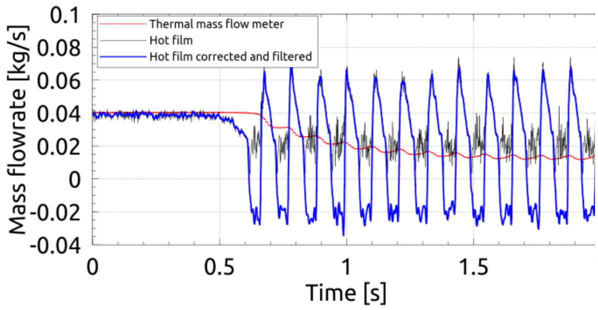

Figure 9: Mass flow rates versus time (test 3)

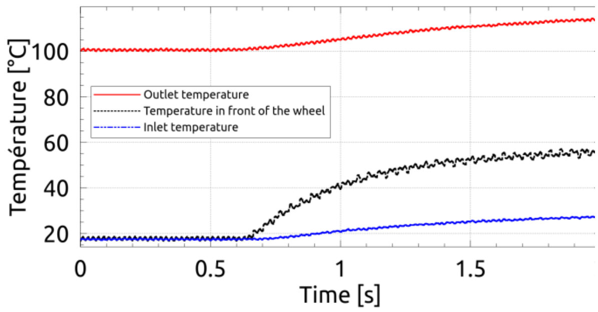

Figure 10: Temperatures versus time (test 1)

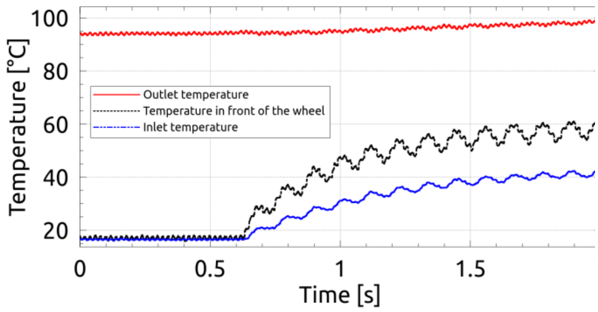

Figure 11: Temperatures versus time (test 3)

Figure 12 and Figure 13 present the amplitude spectrum of the pressures and mass flow signals. Figure 14 and Figure 15 present the amplitude spectrum of the temperatures signals. The FFT (Fast Fourier Transform) is applied on the portion of the signal where there are steady oscillations, after the appearance of surge. For the test carried out without the 0.5 L volume, the frequency of the pressures and flow signals is 23Hz. With the 0.5 L volume added on the outlet pipe, the frequency of the signals is 9 Hz. These frequencies can also be found in the spectrum of the temperature signals. We can also observe in the temperature signals several peaks and specifically one at 51Hz. Results are only presented for tests 1 and 3. Similar results are obtained for tests 2 and 4.

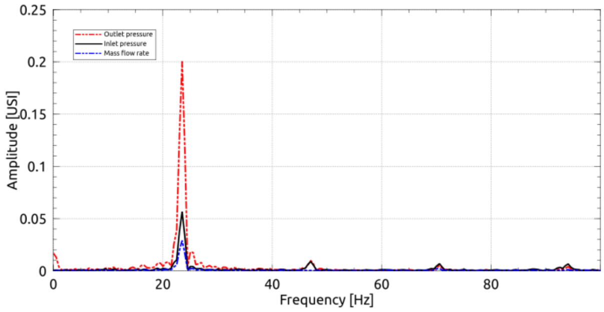

Figure 12: Spectra of pressure and flow rate signals (test 1)

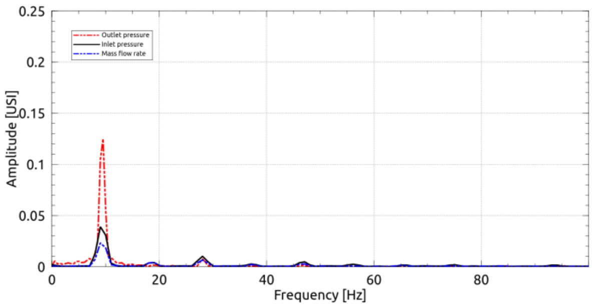

Figure 13 : Spectra of pressure and flow rate signals (test 3)

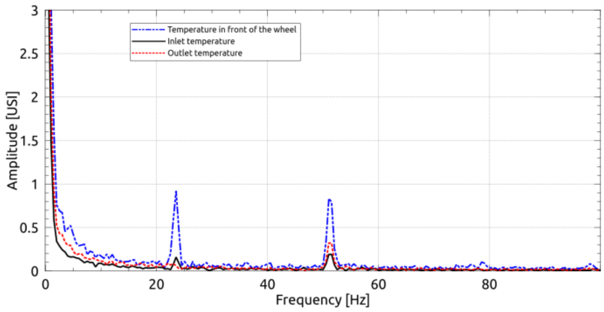

Figure 14: Spectra of temperature signals (test 1)

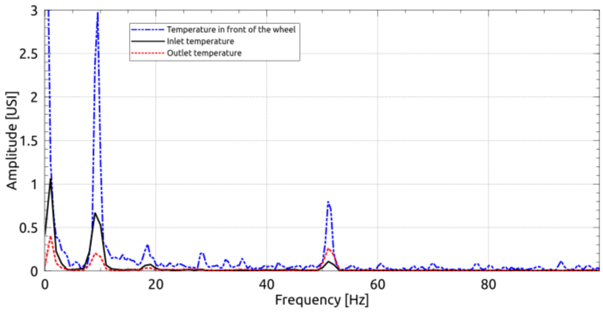

Figure 15: Spectra of temperature signals (test 3)

Figure 16 to Figure 19 present the evolution of pressure ratio versus air flow for the different test starting from initial point. The pressure ratio is filtered using a low pass filter with a cut-off frequency of 100 Hz. The effect of the capacity is obvious on the amplitude of the air flow, but without incidence on the intensity of the pressure ratio.

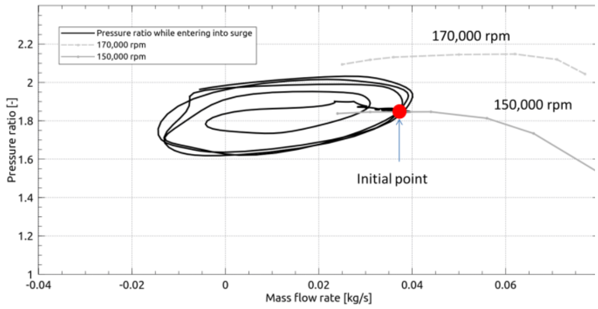

Figure 16: Surge loop (test 1)

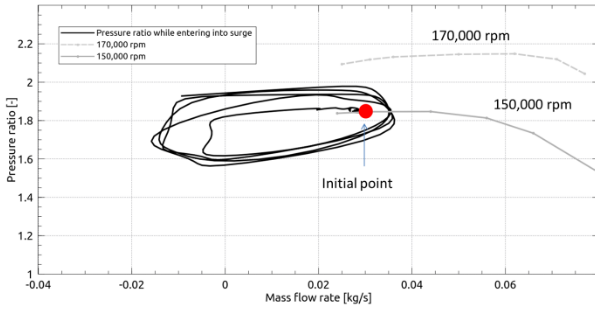

Figure 17: Surge loop (Test 2)

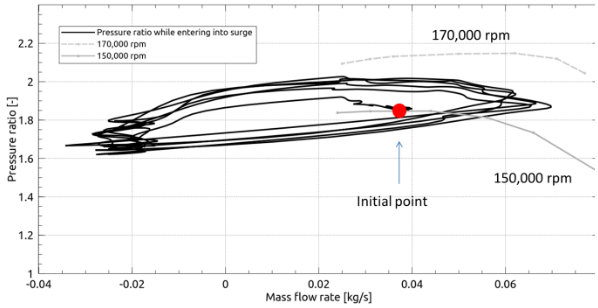

Figure 18: Surge loop (test 3)

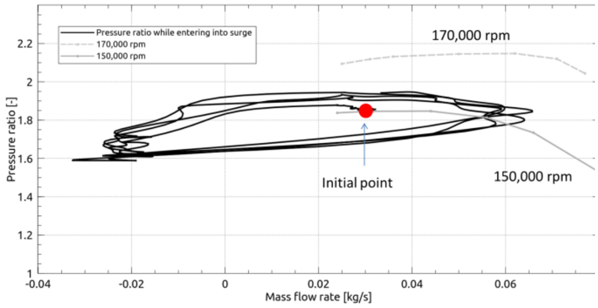

Figure 19: Surge loop (test 4)

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4. Conclusion

Here has been presented a part of our experiments. Complementary tests of suddenly closing the ball valve further from surge point (Mass flow rate = 0.052 kg/s at 150000 rpm) conduct to the same result. Surge appears about 0.2s after turbocharger acceleration. This short delay is mainly due to the fact that in our test procedure the power given by the turbine is almost constant. Then later apparition of surge can be expected if we are able to reduce rapidly the turbine power as for example closing the VNT blades (or opening). Control of VNT is expected for further experiments combine also with control of compressor vane closing.

Concerning experimental results, it has been observed high variations of turbocharger speed in deep surge and even more with a capacity at the compressor outlet. Capacity can be assimilated to a charged air-cooler system. This capacity allows to observe the effect of the downstream and upstream circuit of the turbocharger. As manufacturers give performances of the turbocharger according to test bench, we can see that the operating range of this turbocharger changes when it is used in a vehicle. This phenomenon is confirmed by pressure variation at turbine inlet. Some calculation must be done to link variation of turbocharger speed to torque variation. An optical measurement of turbocharger speed will be added to get more accurate values.

During surge, fluctuation of temperatures has been noticed at main surge frequency. A frequency of 50Hz can also be observed. It seems that this one is due to the conditioning of the signal by the converter which transforms the low voltage of the thermocouple from 0 to 10V signal.
It is planned to replace these converters by others, dedicated to very high speed measurements.

Other experiments have been done on a compressor prototype, defining mild surge by acoustic detection with the operator's ear and deep surge by the occurrence of the surge frequency by a spectral analysis with FFT. Acoustic detection is rather subjective but we have linked this detection with temperature measurements. The same procedure has been applied for deep surge. Results are encouraging and offer a more precise and objective limit.

Surge limit remains difficult to set. Based on our experiments transient measurements look like a good opportunity to define this limit. Surge clearly appears for example by analysing the compressor pressure inlet. Nevertheless, it can be noticed close to this point relatively high variations of air flow which could make difficulties to define precisely the point in terms of air flow and pressure. It could be interesting to carry out investigations for this solution.

In order to obtain a more precise detection method of the surge limit, other signal processing techniques will be tested on pressure, mass-flow rate or temperature signals. Wavelet analysis or Short Fourier Transform could be more efficient to detect the surge appearance than FFT because it allows to analyse signals in very small temporal windows. The Stockwell transform is another way to obtain better temporal and amplitude resolutions of the surge detection.

Finally, modifying the test bench is expected to get closer to a real automotive engine operate range.

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