E3S Web of Conferences **414**, 02016 (2023) https://doi.org/10.1051/e3sconf/202341402016
SUPEHR23

Experimental investigation on the vibrational and fluid dynamics behaviour of a turbocharger compressor in the transition to surge operation

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Abstract. High-speed dynamic centrifugal compressors are widely used both in the modern internal combustion engine design and in advanced pressurized cycles and innovative plant layouts as fuel cell systems. Surge strongly limits the stable operating region of centrifugal compressors in low mass flow rate conditions especially during fast transients. Therefore, it is of great importance to investigate transient system dynamic response of compressor surge evolution and early detection of incipient compressor surge. A specific experimental investigation on compressor surge was carried out at the University of Genoa turbocharger test facility and results are presented and analysed in this paper. The activity consists of steady state and transient measurements used to characterize and identify compressor behaviour in correspondence of surge inception conditions. The frequency and time frequency data analysis have been applied on inflow pressure, anemometric and vibrational signals to identify their contents and so to be able to classify compressor operation as stable or unstable. Synchronous averages performed in the time domain have been identified as a suitable algorithmic tool to detect incipient surge conditions. Anemometric signal analysis allowed to identify intermitting phenomena in deep surge conditions may be related to the rise of a rotation stall condition. The obtained results provide original diagnostic and predictive methods to be integrated in a monitoring system capable of preventing surge and extending compressor operating range, performance and reliability to allow the integration with the other plant components.

1 Introduction

Turbocharger compressors are characterised by operational restriction in off-design conditions due to flow instabilities onset at low mass flow rates.

The need to increase its performance in terms of efficiency and higher compression ratios, makes significant the investigation of dynamic compressor behaviour at low mass flow rate region defining its stability limits. In particular, it is necessary to prevent surge occurrence which results in anomalous fluctuations in flow rate and pressure leading to significant noise and vibration responses, control issues, and potential compressor structural damaging. An important aspect is related to the fact that circuit fluid dynamics characteristics may significantly influence the onset of this unstable condition and in particular the coupled downstream volume may influence sensibly the mass flow rate at which surge occurs. Such experimental evidence is fundamental when compressors are employed in fuel cell pressurization application where complex dynamic mechanisms related to interactions between interposed plenum volume and compressor may arise [1]. For this reason, the onset and early prediction of surge in axial and centrifugal compressors is a key aspect which has been widely investigated in recent decades.

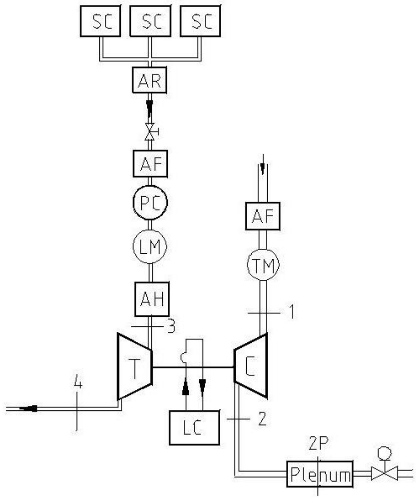
In the open literature a lot of theoretical studies and experimental investigations on surge inception are available, with the aim of achieving the full control of the compressor behaviour in low flow range in order to obtain a wider compressor functionality to supply boost pressure at all required operating conditions [2-6]. Experimental investigations on compressor performance together with the analysis of its vibro-acoustic behaviour provide useful diagnostic tools to enable early reliable detection of low mass flow rate instabilities [7-12]. In these works, the analysis of the compressor vibro-acoustic response during its operation seems to confirm the possibility of developing reliable diagnostic tools to allow a correct early detection of instability phenomena.
In [12] the vibro-acoustic behaviour of two automotive turbocharger compressors has been experimentally investigated with the aim of identifying compressor dynamic response in incipient surge conditions for suitable surge vibro-acoustic precursors definition and validation. In [13] a method for assessing automotive compressor stall margin by exploiting the cross-correlation technique and wavelet analysis is proposed. By means of cross-correlation function analysis, propagation phenomena in the system have been properly detected and their significant energy increase near surge line has been correctly identified. In [14] the smoothed pseudo-Wigner Ville time-frequency distribution is exploited to identify incipient surge conditions in centrifugal compressors by relying on operational vibrational responses measured at significant plant locations.
The reported activity is a further development of previous experimental investigations [12-14] into early surge detection performed by the authors on an automotive turbocharger compressor to correctly detect incipient surge condition by jointly considering vibro-acoustic, inflow pressure and anemometric signals. For this purpose, a large campaign of data acquisition has been conducted at the University of Genoa on a dedicated test rig for components of propulsion systems characterization.
Signal processing techniques based on FFT (Fast Fourier Transform) algorithms were performed on system response signals measured at different measuring sections in the compressor circuit, to maximize information on the current state of the system. Synchronous averages were computed to better identify both deterministic components related to surge cycle or impeller rotation. A peculiar aspect of this paper is to consider different signal processing techniques for incipient surge detection available in the literature and to apply them to signals coming from different typology of sensors (vibration, pressure, anemometric signal). This enabled a more robust assessment of their reliability and the identification of both the strengths and weaknesses of each method in detecting anomalous phenomena occurring under low mass flow rate conditions.

2 Material and methods

The test bench, measuring equipment, investigated component and testing procedures are following described. The signal processing methods are also briefly presented.

2.1 Experimental facility

The experimental campaign was developed on the test rig for components of propulsion systems of the University of Genoa (fully described in [15]) which allows the experimental characterization of single devices or subsystems of propulsion systems circuit. This test bench, schematically shown in Figure 1, allows investigations to be performed under steady, unsteady and transient flow conditions [16-18].



AF	Air Filter	LM	Laminar Flow Meter
AH	Air Heater	PC	Pressure Control
AR	Air Reservoir	SC	Screw Compressor
C	Compressor	T	Turbine
LC	Lubricating Circuit	TM	Thermal Mass Flow Meter

Fig. 1. The turbocharger test facility.

The experimental activity was developed on the turbocharger IHI RHF3 adopted for downsized spark ignition engines. The tested compressor is characterized by a vaneless diffuser; in Table 1, the main geometric characteristics are reported, while in Figure 2 the characteristic curves of the tested turbocharger are shown together with the operating points here considered.

Table 1. Turbocharger geometric characteristics.

Compressor impeller inlet diameter	40 mm
Turbine impeller outlet diameter	33 mm
N° of compressor blades	10
N° of turbine blades	11

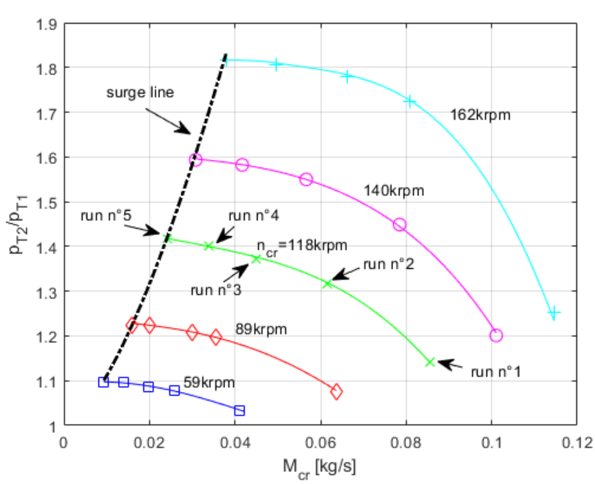


Fig. 2. Compressor characteristic curves.

Dynamic measurements were conducted using a dedicated data acquisition system, which allows to acquire up to 16 different channels with frequencies up to 204.8kHz sampling rate per channel, at the same time. Structural measurements were performed using micro accelerometers located at the compressor inlet, outlet and housing. These probes allow to extend vibration investigation to the higher frequencies, in the range of blade pass frequency (BPF) phenomena. High-frequency response hot-wire anemometric system, calibrated versus the thermal mass flow meter (TM in figure 1, characterized by an accuracy of ±0.9% of measured value and ±0.05% of the full scale), and piezoresistive pressure transducers (accuracy of 0.1% of the full scale) were used to capture instantaneous air mass flow rate and pressure.
The employed accelerometers and microphones have an error of 5% within the frequency range of 5-10 kHz. However, the error remains below ±3 dB below 5 Hz and in the range of 10-50 kHz. The limited accuracy of the vibro-acoustic sensors between 10-50 kHz may be considered acceptable when the absolute value of the signal is not significant, but it is important to note its variation from a stable to an unstable condition. The pressure sensors are characterized by an accuracy of 0.1% of the full scale.

2.2 Signal processing methods

Signal processing methods have been applied on the acquired data set to assess their diagnostic reliability and to validate their robustness in surge detection.
Frequency and time-frequency analysis techniques have been adopted to analyse signal components to identify the system operation and be able to detect incipient surge condition and rotating stall phenomenon [12].
Moreover, synchronous averages have been computed both with linear or energy option. In the first case they allow to put in evidence deterministic contributions related to the reference considered periodic phenomenon (surge cycle or impeller rotation) and reduce frequency contents energy due to both random phenomena and not-synchronous ones. Conversely, energy synchronous averaging better highlights the contributions due to turbulent random phenomena on the deterministic one [19].
A comparison between the two results on the same signal processed in these two cases allows to highlight the amount of random energy in the system, and so this technique seems to have the greatest sensitivity to low mass flow rate instability inception. Frequency analysis on the difference traces between instantaneous and synchronous average signals (properly phased between them with reference to the considered phenomenon) allows to put in evidence and well identify energy frequency contents related to low mass flow rate anomalous phenomena. These phenomena may include rotating stall cells, off-design flow incidence, and distorted fluid distribution within the compressor impeller.

3 Results and discussion

Results obtained using the previously described methods are reported and discussed in the following.
Synchronous averages were initially considered and evaluated on hot-wire anemometric signals and static pressures. To detect incipient surge, the acquired signals in deep surge conditions are initially analyzed to identify specific contents related to this phenomenon. The objective is to investigate whether these characteristics are also present during incipient surge conditions. If so, the aim is to evaluate whether their energy is sufficiently high and reliable to be utilized as surge precursors..
To proceed, the single surge period is identified by analyzing the periodic pressure trend measured in the plenum placed in the compressor outlet circuit. As can be seen from Figure

3, the pressure exhibits a regular trend where the contribution related to surge is predominant, and each surge cycle can be easily identified through the time-domain analysis of the signal.

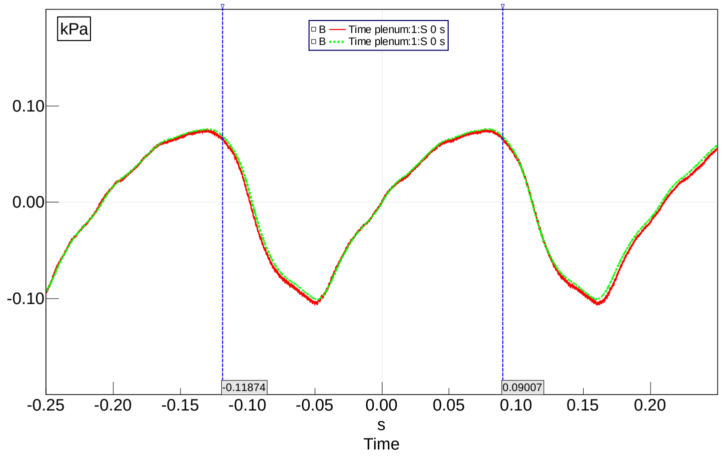


Fig. 3. Pressure time history measured at the downstream outlet plenum volume (red trace -> instantaneous trace; green trace -> cycle-averaged trace)

In figures 4 and 5 anemometric and pressure signals measured at the compressor inlet (measuring section 1 in figure 1) are respectively reported. In both cases, the red trace represents the instantaneous signal, while the green trace represents the synchronous linear cycle-average signal evaluated with respect to 80 deep surge cycles.. The two traces are reported in phase with reference to the observed phenomenon. In the instantaneous anemometer signal (red trace), within a single surge cycle, a time interval is clearly well distinguishable where the flow rate presents strong irregularities, followed by remaining instants where the trace is characterized by a more regular and smooth trend. In Figure 4, the two blue dashed cursors delineate an entire deep surge cycle, within which an initial segment can be observed. In this segment, the instantaneous trace exhibits pronounced irregularities, and its trend deviates significantly from that of the averaged signal (green trace).

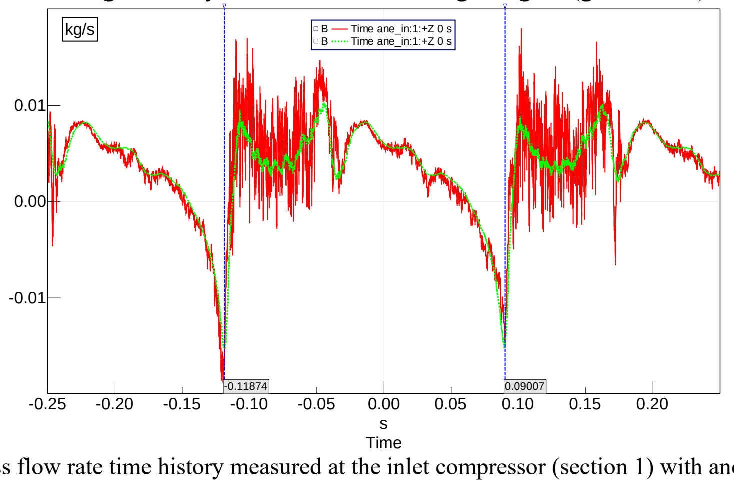


Fig. 4. Mass flow rate time history measured at the inlet compressor (section 1) with anemometric sensor (red trace -> instantaneous trace; green trace -> averaged trace)

Figure 5 shows the pressure signal measured at the compressor inlet reported in phase with the previous anemometric signal. In the instantaneous pressure signal, it is possible to identify

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time instants within the surge cycle where its trend exhibits strong irregularities, corresponding to those in which the anemometer signal presents irregularity too. However, in this case, the irregularities seem to persist over the entire cycle without reducing their energy in the rest of the cycle.
This may be related to reflection phenomena present within the system and characterized by low damping, which do not decay within an entire surge cycle and persist in the pressure trace measured continuously. As for anemometric signal, also in this case, there are evident significant contents related to non-synchronous phenomena with the surge phenomenon. This is indicated by non-negligible deviations between the instantaneous time history (red trace) and the averaged one (green trace).

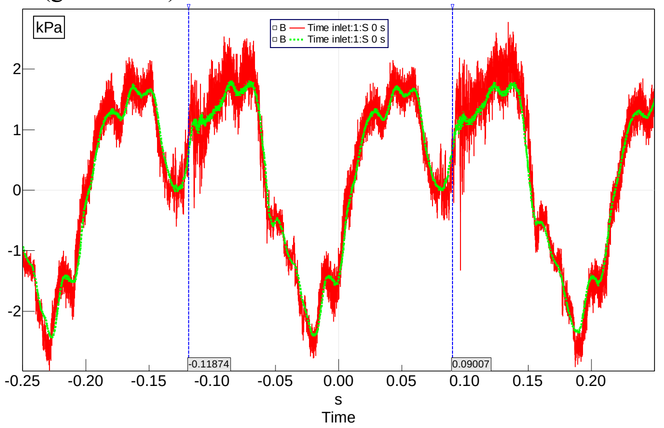

Fig. 5. Pressure time history measured at the inlet compressor (section 1)
(red trace -> instantaneous trace; green trace -> averaged trace)

To analyze the nature of this contribution with a marked intermittent characteristic within the deep surge condition, an FFT analysis was carried for both the anemometer and the pressure signals during each surge cycle, where this content is significantly present.
To better identify the characteristics of this contribution in the acquired signals, the difference between the synchronous averaged signal and the instantaneous one is calculated. In this way, the resulting trace (instantaneous minus linear average) is mainly related to random contents and components related to phenomena with periods different from that of the surge.
In figure 6 a trace difference is reported, the double cursor indicates a single deep surge cycle. The considered extract starts from the left single cursor trace and last for about half period. The previous acquisition characterized by 80 deep surge cycle is considered and for each surge cycle the difference trace spectrum is computed and FFT is evaluated on the part of the cycle where strong irregularities are evident.

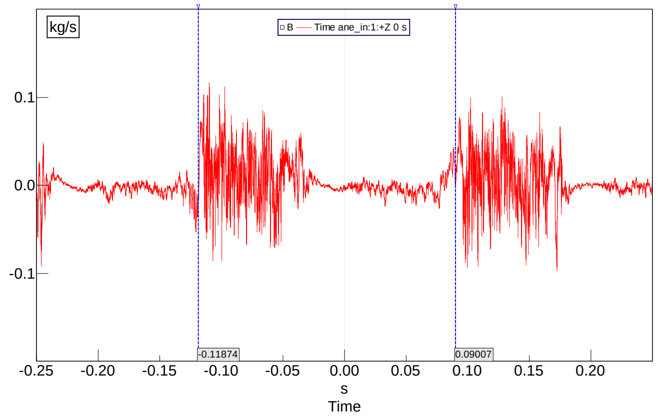

Fig. 6. Difference trace between the synchronous averaged and instantaneous ones of the anemometric signal measured at the compressor inlet.

Figure 7 shows the computed FFT. Two well defined peaks at 610Hz and 1260Hz can be identified, with the frequency of the second peak being roughly double of the first. These peaks indicate the presence of a sub-synchronous phenomenon, which may be attributed to the onset of an unstable condition in the vaneless diffuser compressor. This typically occurs when the compressor passes from an incipient surge condition, such as rotating stall conditions, to a deep surge condition, where backflow occurs within the compressor. In the considered condition, the impeller rotation frequency is about 1X=2kHz.

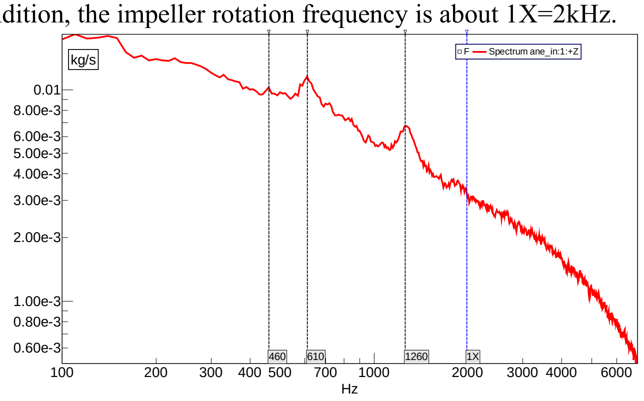

Fig. 7. FFT of the difference trace between the synchronous averaged and instantaneous ones of the anemometric signal measured at the compressor inlet.

Indeed, the considered turbocharger centrifugal compressor is equipped with a vaneless diffuser, and for this kind of radial turbomachinery, rotating stall inception mechanism is peculiar. A similar type of compressor was investigated in [12-14], where the vaneless diffuser rotating stall (VDRS) was observed at a frequency level of approximately 0.25-0.35 times the rotational speed, which is consistent with previous results.
The pressure signal at the compressor inlet is processed in the same way. Figure 8 shows the difference trace in a time interval corresponding to two deep surge cycles (the double cursor identifies a single surge cycle with the same start and end instants adopted in the previous figures).

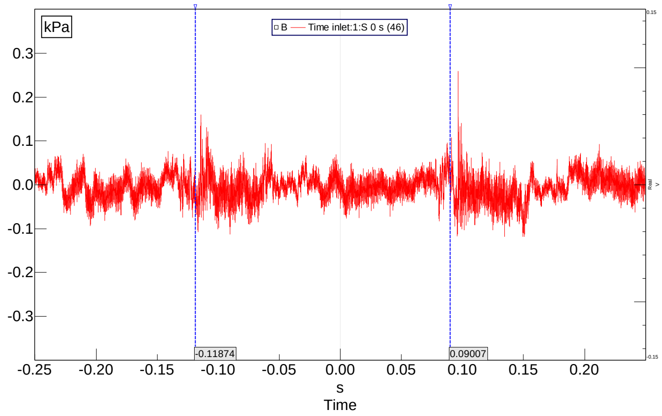

Fig. 8. Difference trace between the synchronous averaged and instantaneous ones of the pressure signal measured at the compressor inlet.

Figure 9 shows the computed FFT. In the case of pressure signal, it is possible to note how the obtained spectrum is characterized by a higher number of peaks than the anemometer case.

This could be justified by perturbations reflection phenomena and system acoustic modes excited by the surge phenomenon which significantly affect the pressure values and are well detected by the pressure transducers. The same phenomena seem to affect in a less marked way the mass flow rate, as appears from the analysis of the signal from the anemometer probe.

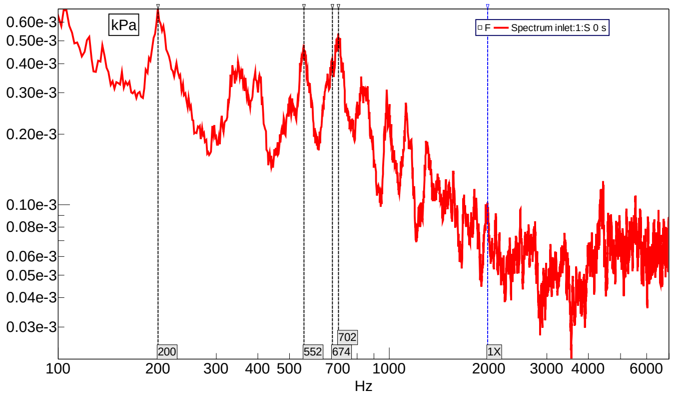

Fig. 9. FFT of the difference trace between the synchronous averaged and instantaneous ones of pressure signal measured at the compressor inlet.

In the following a comparison between two operating steady conditions is reported: "run n° 2" corresponds to the stable operation approaching the compressor maximum efficiency and "run n° 5" corresponding to the last stable condition before surge and can be considered as an incipient surge operating condition. Figure 10 shows both linear and energy synchronous average spectrum of the mass flow rate, as assessed using the anemometer signal, with reference to the rotation of the compressor impeller.

Synchronous rotational averages were computed to better identify both deterministic components related to impeller rotation and random ones. Both linear and energy averages were performed to distinguish between spectral contents related to rotation impeller from random contributions and components related to fractional orders. Indeed, linear

synchronous averaging reduce frequency component energy due to both random phenomena and sub-synchronous ones.
Spectra in run 2 and 5 appear significantly different when energy average is adopted. In the incipient surge condition (run 5) sub-synchronous phenomena seem to rise significantly, with frequency values very similar to those of the intermittent phenomena previously identified in the deep surge condition. Otherwise, adopting linear averages, the computed spectra appear very similar in the two considered operating conditions (runs 2 and 5) to indicate the phenomena that occur in the compressor near low mass flow rate instability conditions are mainly characterized by non-synchronous contents.
This could be justified by the establishment of rotating stall, a typically sub-synchronous phenomenon which can be captured when the compressor is approaching the low-flow instability region.

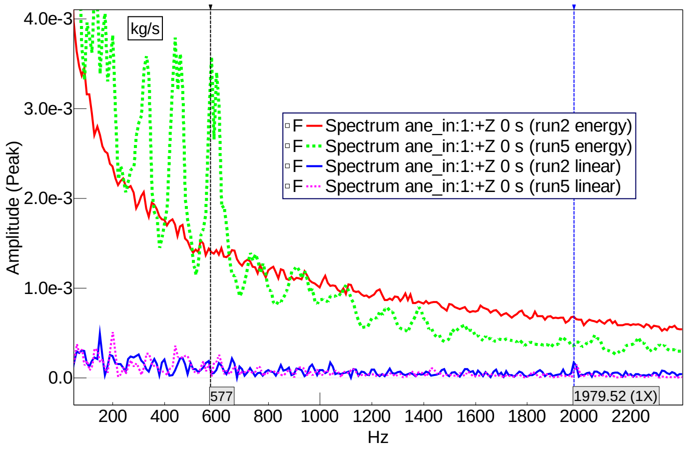

Fig. 10. Linear and energy synchronously averaged spectra of the anemometric signal measured at the compressor inlet in stable and incipient surge conditions.

Figure 11 shows the energy synchronously averaged spectra with reference to the rotation of the compressor impeller computed on pressure signal measured at the compressor inlet. Similar to the previous case, the increase of specific contents in the incipient surge condition is well detectable.

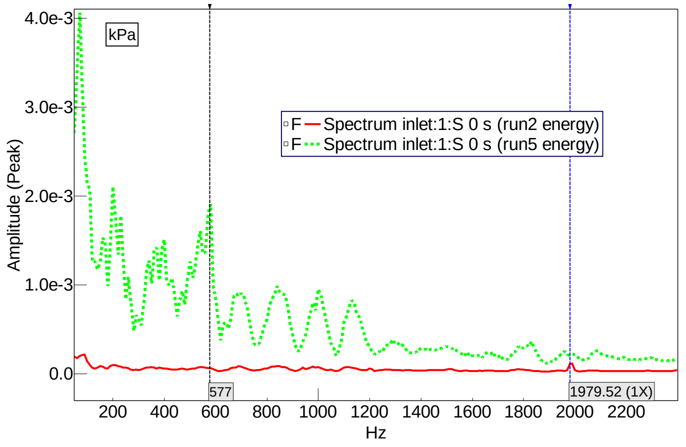

Fig. 11. Energy synchronously averaged spectra of the pressure probe measured at the compressor inlet in stable and incipient surge conditions.

Vibration data were recorded through a high sample frequency value (100 kHz) to investigate vibrational and acoustic response in high frequency domain close to the blade pass frequency (BPF).
Figure 12 shows high frequency components of the synchronous linear average spectra measured on compressor housing in radial direction from stable (operating run 2, red trace) to incipient surge (operating run 5, green trace).
It is possible to note that the frequency peak associated with the BPF (dotted blue line cursors at 10kHz and 20kHz for the BPFs without or with splitter blades) becomes less marked moving from point 2 to point 5. Near unstable conditions, BPF component seems to lose energy.

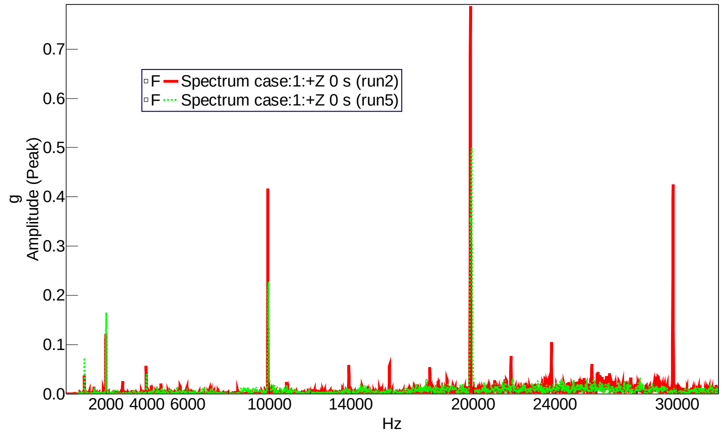

Fig. 12. Linear synchronously averaged vibration spectra in stable and incipient surge conditions.

Figure 13 shows the energy-averaged spectra of the previous two signals. Energy synchronously averaged vibration spectra in incipient surge condition is characterized by significant side bands in correspondence of the BPF probably related to modulation phenomena rising in the system.
Side bands are not significant when linear averaged is adopted, thus indicating the involved phenomenon is not synchronous and therefore is removed adopting a linear averaged process. This seems to further confirm the hypothesis of the rotating stall sub-synchronous phenomenon occurrence in conditions close to the surge. This is evident at the BPF considering only main compressor blades (5X) close to 10kHz. Also at the BPF which takes into account also the splitter ones (10X), this spectrum characteristic is present even if in a less marked way.

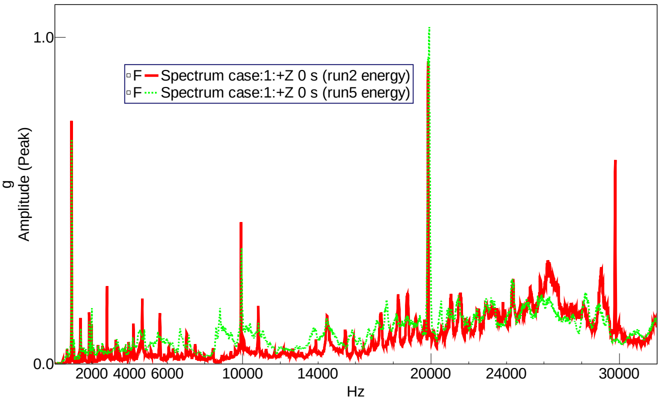

Fig. 13. Energy synchronously averaged vibration spectra in stable and incipient surge conditions

4 Conclusion

This study presents the results of an experimental analysis of a turbocharger centrifugal compressor behaviour with special reference to the transition from a stable condition to the low flow instability region. In this work the diagnostic capability of synchronous average evaluated on fluid dynamic and vibro-acoustic responses to detect incipient surge conditions has been evaluated.

This technique, used in the linear or energy mode, allows a clear distinction between synchronous contents related to the considered phenomenon (such as deep surge or impeller rotation) and random or differently periodic contents, enabling the identification of phenomena that arise due to the compressor approaching a condition of low instability at low flow rate.

In the anemometric signals it is possible to well detect rotating stall intermittency in deep surge conditions by observing the trend of instant and synchronous averaged response traces. Moreover, time frequency analysis performed on the acquired signals allows to detect rotating stall intermittency and its frequency characteristic contents when this signal processing technique is set with a good temporal resolution.

High frequency analysis in the range of BPF jointly with synchronous average computation, seems to be an effective tool in incipient surge detection.

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