Early surge detection on a turbocharger used to pressurize a SOFC plant emulator

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Abstract. High-speed centrifugal compressors are commonly exploited to pressurize fuel cell-based hybrid energy systems. In such complex plants, because of significant interposed volumes due to fuel cells, dynamic compressor response can induce severe vibrations caused by low mass flow rates instability. In particular, surge strongly limits centrifugal compressors stable working region when moving towards low mass flow rate due to a change in system operating point. Consequently, a complete system identification is performed in order to adequately characterize compressor dynamic response for early surge detection. To this goal, a tailored experimental activity has been carried out at the Thermochemical Power Group of the University of Genoa on a vaneless diffuser compressor turbocharger used for the pressurization of an innovative solid oxide fuel cell (SOFC) emulator plant. Several post-processing methods have been performed on system vibro-acoustic responses to better predict and classify compressor status as stable or unstable. The obtained results provide original diagnostic insights for monitoring systems capable of preventing surge and other low mass flow unstable phenomena, such as rotating stall cells inception. Low mass flow rate fluid-dynamic instabilities prevention can extend compressor operating range, performance, and reliability to allow better integration with other plant components.

1 Introduction

A crucial property of turbocharger compressors is their operational limit in off-design conditions; it is due to fluid-dynamic instability onset at low mass flow rates and to choke phenomenon at high mass flow rates. The need to increase performances, both in terms of efficiency and compression ratios, makes the correct identification of centrifugal compressors stability limits significant. In particular, surge must be avoided since it causes anomalous fluctuations in mass flow rate and pressure; moreover, it can induce anomalous noise and vibration responses, control problems, and likely compressor structural damaging. Circuit fluid dynamic characteristics significantly influence surge onset and in particular the volume attached downstream of the compressor considerably affects the mass flow rate at which it occurs. Such experimental evidence is fundamental when compressors are employed in fuel cell pressurization application where complex dynamic mechanisms related to

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interactions between interposed plenum volumes and compressor may arise. For such reasons, early surge detection in axial and centrifugal compressors coupled with large volumes is still a key aspect which has been widely investigated in recent decades.

In the literature there are numerous theoretical studies and experimental investigations about surge inception where the aim is to allow full control of compressor behavior in the low flow range; indeed, the ultimate goal is to obtain a wider compressor functionality to supply boost pressure at all the required operating conditions [1-5]. Experimental investigations about compressor performance together with analysis of its vibro-acoustic behavior provide useful diagnostic insights; indeed, they enable a reliable early detection of low mass flow rate instabilities [6-10]. Munari et al. [6] investigated aeronautic turboshaft gas turbine axial-centrifugal compressor behaviour by developing an experimental activity in operating conditions close to surge line. The test field data were investigated showing both performances and vibro-acoustic response variation towards and during surge. Kabral et al. [7] developed a thorough investigation into compressor stall and surge inception by means of an acoustic two-port model. The authors found that flow instabilities due to rotating stall generate remarkable sound pressure which significantly affects overall system acoustic response. In [8] the authors experimentally investigated vibro-acoustic signature of two automotive centrifugal compressors; the goal was to identify peculiar contents onset in compressor response in incipient surge conditions for early surge detection. Reggio et al. [9] introduced an innovative tool for real-time surge prevention in advanced gas turbine cycles which is described in detail and implemented. The software was validated with data from a test rig made up of a micro-turbine connected with a modular vessel. Three peculiar plant configurations characterized by different volume sizes between turbine compressor outlet and recuperator inlet were investigated; the software developed was able to successfully predict surge inception in all operating conditions tested. In [10] the authors developed a vibro-acoustic experimental investigation into fluid-dynamic instability occurring in a compressor made up of six axial stages and a centrifugal one. A sub-synchronous spectral content was detected in system structural response at a low mass flow rate; its energy considerably increased when the valve used to tune external circuit characteristic curve was nearest its closure position.

In [11] an investigation into instability phenomena with particular focus on surge and rotating stall in case of a turbocharger ported shroud compressor is discussed. Combined inflow pressure measurements together with flow visualizations using phase-locked PIV technique allowed detection of self-excited non-linear phenomena in pressure signal during surge.

In [12] the authors found that significant acoustic energy was detected in system responses near Helmholtz frequency when approaching surge. Moreover, in [13] the authors showed that system vibro-acoustic response exhibits a dominant spectral content in the sub-synchronous frequency range arising close to incipient surge conditions that may be due to rotating stall onset.

In [14] an investigation into surge signature of a single stage centrifugal compressor was performed at different inlet tip speed conditions (subsonic, transonic, and supersonic). Both steady state performance data and those of dynamic pressure were recorded. At higher angular speeds, with the impeller leading edge tip relative Mach numbers higher than one, the inducer stalls at a much lower incidence angle due to the greater losses ascribable to increasing Mach number.

In [15] cyclostationary analysis was applied to system vibro-acoustic responses in order to deepen knowledge of fluid-dynamic instability phenomena occurring at low mass flow rates. Such a signal processing technique proved its reliability in rotating stall cell detection and early surge identification. Moreover, surge precursors based on time, angle and frequency domain analyses were defined showing a good predictability with respect to surge approaching. The centrifugal compressor investigated is the same considered in this work used to pressurize the same SOFC emulator plant. Indeed, the reported activity is a further development of a previous experimental investigation into early surge detection performed by the authors on the same SOFC emulator plant [15].

2 Test rig description and measurement system

The experimental facility used in this research activity and the measurement system employed are described in the following, respectively.

The test campaign to acquire data for early surge identification was carried out on the turbocharged SOFC emulator plant located at the IES (Innovative Energy Systems) laboratory on Savona campus [16]. The dedicated experimental facility is made up of a pressure vessel boosted by means of a commercial turbocharger which pressurizes the plant. The pressure container is built with a multilayer structural design and is connected to a burner (CCM) to reproduce expected SOFC thermal regime and to inert ceramic materials to take into account its thermal capacitance. Moreover, said test facility features a recuperator (REC) to reproduce SOFC thermal recovering system, an air/water heat exchanger (Ex) in order to recreate and control environmental temperature, and a further burner to start-up the plant (CCS).

The facility considered features supplementary auxiliary systems devoted to test and control duties: (i) the water injection duct (piloted by the VW valve) to cool down the recuperator inlet pipe (hot part) in case of extreme temperature, (ii) the CO_2 injection duct to reproduce functioning with biogas of various compositions (piloted by the VCO2 valve), (iii) the start-up air pipe to supply compressed air in ignition conditions (piloted by the VSU valve), (iv) the compressor/turbine bypass (piloted by the VB valve - VBa and VBb manual valves allow two choices) to tune angular speed together with SOFC temperature, (v) the recuperator bypass duct (piloted by the VRB valve) for a further thermal tuning choice in start-up/shutdown transients, (vi) the bleed duct (piloted by both controlled - VSRb - and on/off valves - VSRa), and (vii) a further valve in the principal duct (VM) to control air through particular start-up/shutdown conditions. Moreover, the test facility features sensors devoted to mass flow rate, pressure, and temperature detection in various air-line measurement points. An eddy current sensor placed near the compressor impeller is chosen for turbocharger angular speed detection [16]. A control system devised within LabVIEW® is exploited to perform the experimental investigation on said plant. An automotive Garrett turbocharger GT1238Z for downsized spark ignition internal combustion engines is employed in the system. The dynamic compressor features a vaneless diffuser, while its rotor wheel features six loaded blades and six further splitter ones; the turbine features nine blades. Vibro-acoustic measurements were performed by relying on a Siemens Scadas portable data acquisition system, which allows sampling of frequencies up to 204.8 kHz for each channel, simultaneously. Vibrational signals were collected by exploiting mono-axial accelerometers placed both at the compressor inlet and at its outlet plus a micro-accelerometer (with resonant frequency > 95 kHz and measurement uncertainty of ±3 dB, from 5 Hz to 65 kHz) located on the compressor housing in axial direction with reference to its volute [15]. Said micro-accelerometer can enlarge vibration observation field up to higher frequencies, in such a way that Blade Pass Frequency (BPF) range can be investigated. Sound pressure signals were acquired by exploiting a pre-polarized microphone with linear frequency response in the frequency range 2-25 kHz (measurement uncertainty of ± 2 dB, from 3.15Hz to 25 kHz).

The sample rate was set to 204.8 kHz for all sensors: tachometer (to obtain an accurate evaluation of instantaneous angular speed), accelerometers, and microphone. In this way, system response at high frequency could be investigated up to BPF range, depending on each sensor dynamic property; this allowed to observe BPF energy trend variations when compressor operating condition is approaching surge starting from stable behavior [17].

3 Results and discussion

The results obtained by relying on the previously described test rig and measurement system are discussed in detail hereinafter.

3.1 Turbocharger Vibro-acoustic signature analysis in stable conditions

Before performing surge transients vibro-acoustic analysis, system dynamic behavior has been experimentally investigated far from surge in order to characterize its vibro-acoustic signature in stable conditions. To this goal, compressor angular speed run up have been performed from about 50krpm up to 260 krpm. Vibro-acoustic measurements acquired in these plant operating conditions are essential to identify the dominant frequency components in system operating response and to correlate them with the associated physical mechanisms.

Fig. 1 reports a time-frequency map of compressor housing microphone signal performed in run-up conditions. Decades representation (log scale) is adopted for both abscissa (frequency) and ordinate (compressor angular speed) axes. The third dimension represents signal energy. Engine order cursors are also reported to correlate the detected spectral contents to the multiples of compressor shaft angular frequency (1X order). Indeed, the synchronous component (i.e. 1X order) is detectable during the whole run-up test (please refer to order cursor 1) which is mainly related to residual mechanical imbalance in the shaft. Moreover, the investigated turbocharger is supplied with floating ring radial bearings; therefore, the onset of sub-synchronous frequency components (below shaft angular frequency) may be related to bearings floating ring whirling or whipping phenomena. During the entire investigated run-up test, the spectral content characteristic frequency related to the bearing rings stays always between two values shown in Fig. 1 by the red dashed cursors associated to 0.2X and 0.4X orders. At lower speeds (60-70 krpm) the spectral content characteristic frequency is near order 0.4X, while at higher speeds it is near order 0.2X.

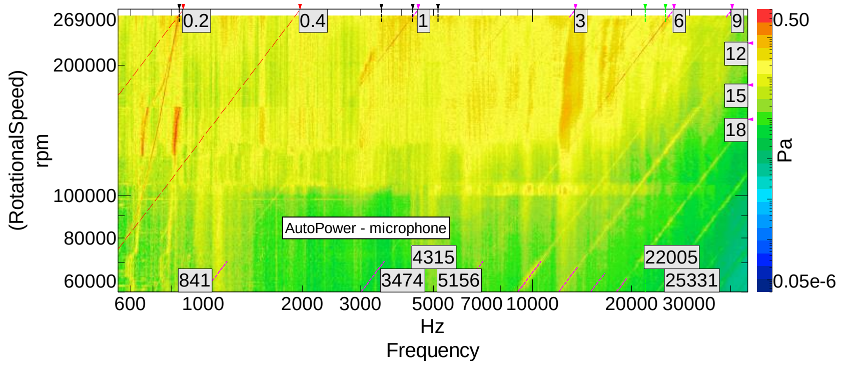

Fig. 1. Time-frequency analysis (STFT) of microphone response signal in run up conditions.

When moving towards high angular speeds, some spectral contents increase their energy, which are probably due to modulation phenomena of the 1st sub-synchronous component with respect to 1X order; indeed, at the maximum angular frequency (4315 Hz), sidebands shown by the black dotted short line cursors appear at 4315-841 = 3474 Hz and 4315+841 = 5156 Hz. Furthermore, in the colormap representation orders 6X and 12X are well evident (please refer to the magenta dotted short line cursors). The spectral content related to order

12X exhibits lower energy than the one of order 6X: these frequency components may be related to compressor blade passage phenomenon; indeed, compressor rotor features six main blades (6X) plus six splitter blades (6+6=12X). Blade pass frequency (BPF) related to turbocharger turbine should induce 9X order energy increase (turbine features 9 blades) with its double multiple (18X order). 9X order exhibits two sidebands, which are likely related to modulation phenomena on 9X order due to compressor BPF (please see magenta dotted short line cursors at9X-6X = 3X and 9X+6X = 15X). Finally, high frequency components (please see cursors at 22 kHz and 25.3 kHz) can be identified at high angular speeds which may be ascribable to combustion spectral contents: further detailed investigations will be conducted to confirm such assumption.

3.2 Surge transient analysis

The analyzed surge transients have been obtained by closing gradually the valve between the compressor and the turbine; meanwhile, vibro-acoustic response signals have been acquired. In the following, the results obtained by exploiting Short-time Fourier Transform (STFT) time-frequency representation on a specific surge transient are considered. Anyway, analogous results were found for the other acquired surge transients, thus confirming the reliability of such technique for system identification.

The investigated transient features an angular speed trend ranging from about 200krpm to system shutdown, after compressor enters surge cycles. Fig. 2 shows turbocharger angular speed (red line) and radial accelerometer (green line) time history for the entire reference surge transient. After a stable operating condition is reached, turbocharger compressor speed decreases to move towards the surge line; afterwards, a series of surge cycles occurs. Marked oscillations in angular speed signal as well as in compressor structural response due to surge occurrence are evident when the system enters instability, which then slowly disappear when the plant is shut down to avoid structural damaging.

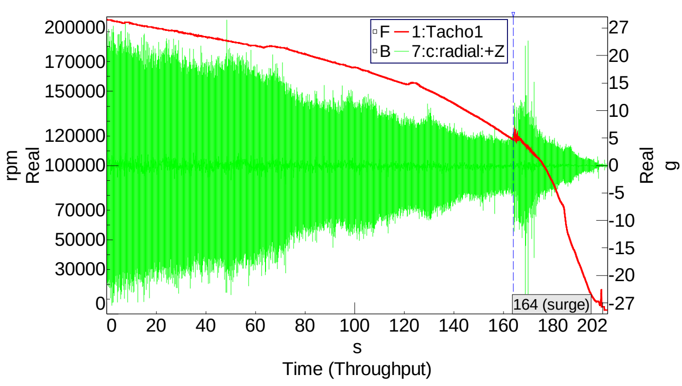

Fig. 2. Time-history of radial accelerometer and tachometer signals in run up conditions.

In Fig. 3 a time-frequency analysis (STFT) of structural signal is reported for the whole reference surge transient up to compressor BPF, thus including both sub-synchronous spectral contents, synchronous frequency component and its more significant multiples; this representation allows to better identify signal components energy variations with time in order to investigate how spectral contents are affected by a variation in system operational condition during the reference surge transient. Such colormap representation exploits abscissa axis normalization by taking the ratio of a general frequency value with the one of angular speed (1X order). With this normalization, the spectral contents relevant to any engine order are found at a fixed abscissa value during the reference surge transient, characterized by variable angular speed. Indeed, the time-frequency map spans in the normalized frequency range between 0 and 12X order and is centered at roughly 6X order.

Sub-synchronous spectral contents increase their energy during the reference transient just before entering surge (please refer to green dotted cursors). Their energy increase is marked in correspondence with compressor mass flow rate reduction in the time interval 123-164 s (refer to Fig. 3). This suggests that they may be related to the onset of low mass flow rate fluid-dynamic instability phenomena such as rotating stall cells.

In incipient surge conditions (roughly the last 40 s of the reference transient before surge cycles happen, where the mass flow rate decreases significantly), 6X order varies its energy and so does even 12X order. The spectral content equivalent to order 6X modifies its amplitude and its response energy far from surge is distributed in a wider frequency range. The onset of these spectral contents may be attributable to fluid flow anomalous incidence angle at the impeller inlet when compressor is moving towards surge. In such operating conditions non-deterministic phenomena seem to arise with a not well-defined cyclic nature and hence response signals energy distribution changes its frequency pattern. Finally, 9X order is also well identifiable in all the surge transient and modifies its energy close to surge.

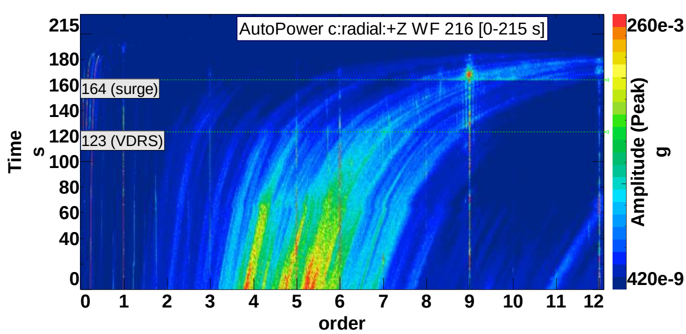

Fig. 3. Time-frequency analysis (STFT) of radial accelerometer signal during surge transient

In the following, frequency sections will be extracted from the previous colormap, thus resulting in 2D charts obtained by cutting the 3D chart at a constant frequency (order) level. In Fig. 4 time trends of vibrational and acoustic response signals are presented during the reference surge transient for 0.5X order, which is representative of the energy of the whole sub-synchronous frequency band, together with angular speed trend. More in detail, green line represents acoustic system response, whereas blue line stands for radial accelerometer structural signal. Both vibro-acoustic response signals exhibit a similar behavior characterized by a progressive amplitude decrease coherent with that of angular speed, until a sudden energy increase occurs (see dashed cursor). Indeed, by moving towards the surge line, vibro-acoustic energy increases due to the arising fluid-dynamic instability which may be ascribable to vaneless diffuser rotating stall (VDRS) onset, as already observed before. Afterwards, another peak in vibro-acoustic system response is found when surge cycle begins (see dotted cursor), which is more evident in acoustic response signal than in structural one.

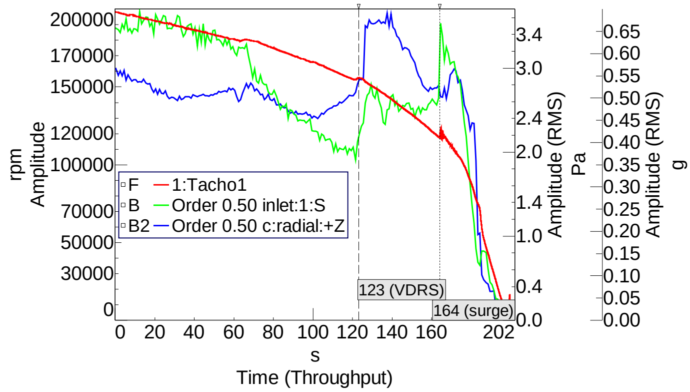

Fig. 4. Accelerometer and microphone sub-synchronous energy trend in the surge transient

The increase of sub-synchronous energy before surge inception may be regarded as a surge precursor, as it is not influenced by residual mechanical imbalance and therefore it is more suited to identify rotating stall cells onset.

In the following, the frequency sections (order) analysis will be performed even on compressor blade pass frequency, to assess how surge onset can influence the energy of its associated frequency components, equivalent to 6X order (compressor main blades pass frequency). In Fig. 5, time trends of 6X order is reported for both microphone signal and axial accelerometer one, together with system angular speed. Even in this case, a sudden increase in vibro-acoustic energy can be identified in incipient unstable conditions before surge occurrence. Indeed, the trend of vibro-acoustic response signals is characterized by a maximum, after which signals energy stabilizes to a lower level until the system is stopped after surge onset. Even in this case, the increase of BPF energy before surge onset may be regarded as a surge precursor based on vibro-acoustic signals energy, which is obtained from an experimental setup based on not intrusive probes like accelerometers and microphones.

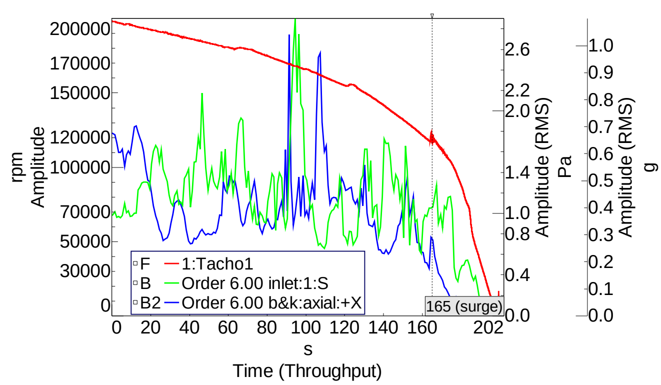

Fig. 5. Accelerometer and microphone compressor BPF energy trend in the surge transient

CONCLUSIONS

This article reports the results obtained about early surge detection in order to find adequate precursors (research and validation) obtained by relying only on vibro-acoustic signals; vibro-acoustic analysis was performed in the context of an experimental activity conducted on a turbocharger equipped with a centrifugal compressor in a solid oxide fuel cell emulator plant. Indeed, Pressurized SOFC emulator plants are characterized by an increased surge risk during their operational transients due to the interposition of a significant pressurized volume downstream the compressor. Due to this reason, the research of reliable surge precursors based on cheap and not intrusive probes is a good way to develop robust anti-surge control systems to guarantee the reliability and safety of this kind of systems.

Time-frequency analysis can better detect sub-synchronous specific contents at medium frequency levels, which may be attributable to likely rotating stall cells onset; moreover, high frequency phenomena related to compressor blade pass frequency are identifiable by applying STFT to both vibrational signals and acoustic ones. Moreover, this post-processing method can identify rotating stall intermittency in incipient surge conditions. Through STFT, the diagnostic information about rotating stall may be obtained considering only the sub-synchronous frequency components extracted from vibro-acoustic signals without investigating dynamic pressure ones; vibro-acoustic energy in the sub-synchronous range together with the one relevant to compressor blade pass frequency may be regarded as reliable anti-surge signals from which quantitative indicators like their RMS value can be extracted .

The surge precursors obtained will be considered to develop a robust control and diagnostic system capable of preventing surge on compressors installed in complex energy plants. Future work will consider further signal processing techniques to extract diagnostic contents from system response signals to define additional surge precursors and obtain a more reliable early detection of incipient fluid-dynamic instabilities.

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References

1. Greitzer, E.M., “Surge and Rotating Stall in Axial Flow Compressors. Part I: Theoretical Compression System Model”. Journal of Engineering for Power, **98** (1976) 190-198
2. Arnulfi G.L., Giannattasio P., Giusto C., Massardo A.F., Micheli D., Pinamonti P., “Multistage Centrifugal Compressor Surge Analysis. Part I: Experimental Investigation”, Journal of Turbomachinery, Vol. 121, April 1999, pp. 305-311, 1999
3. Cravero, C., Marsano, D.; “Criteria for the Stability Limit Prediction of High Speed Centrifugal Compressors with Vaneless Diffuser. Part I: Flow Structure Analysis”, ASME Turbo Expo 2020, ASME paper GT2020-14579, London, UK, 22-26 June 2020
4. Cravero, C., Marsano, D., “Criteria for the Stability Limit Prediction of High Speed Centrifugal Compressors with Vaneless Diffuser. Part II: The Development of Prediction Criteria”, ASME Turbo Expo 2020, ASME paper GT2020-14589, London, UK, 22-26 June 2020
5. Cravero, C., Leutcha, P.J., Marsano, D., “Simulation and Modeling of Ported Shroud Effects on Radial Compressor Stage Stability Limits”. Energies 2022, 15, 2571. https://doi.org/10.3390/en15072571
6. Munari, E., Morini, M., Pinelli, M., Spina, P.R., Suman, A., “Experimental Investigation of Stall and Surge in a Multistage Compressor”, ASME Paper GT2016-57168, ASME Turbo Expo 2016, Seoul, South Korea
7. Kabral, R., Åbom, M., “Investigation of turbocharger compressor surge inception by means of an acoustic two-port model”. Journal of Sound and Vibration 412 (2018), pp. 270-286
8. Marelli, S., Silvestri, P., Usai, V., and Capobianco, M., “Incipient Surge Detection in Automotive Turbocharger Compressors,” SAE Technical Paper 2019-24-0186, 2019, doi:10.4271/2019-24-0186

9. Reggio F., Silvestri P., Ferrari M.L., Massardo A.F., “Operation extension in gas turbine-based advanced cycles with a surge prevention tool”, (2022) Meccanica, 57 (8), pp. 2117-2130
10. Munari, E., D’Elia, G., Morini, M., Mucchi, E., Pinelli, M., Spina, P.R., 2018, “Experimental Investigation of Vibrational and Acoustic Phenomena for Detecting the Stall and Surge of a Multistage Compressor”, Journal of Engineering for Gas Turbines and Power, 140 (9)
11. Guillou, E., Gancedo, M., Gutmark, E., “Experimental Investigation of Flow Instability in a Turbocharger Ported Shroud Compressor”, Journal of Turbomachinery 2016, Vol. 138/061002-1
12. Dehner, R., Figurella, N., Selamet, A., Keller, P., Becker, M., Tallio, K., Miazgowicz, K., Wade, R., “Instabilities at the low-flow range of a turbocharger compressor”, SAE Int. J. Engines 6 (2) (2013) 1356e1367, https://doi.org/10.4271/2013-01-1886
13. Zhenzhong, S., Wangzhi, Z., Xinqian, Z., “Instability detection of centrifugal compressors by means of acoustic measurements”, Aerospace Science and Technology 82–83 (2018) 628–635
14. Lou F., Harrison H. M., Key N. L. “Investigation of surge in a transonic centrifugal compressor with vaned diffuser: part 1 – surge signature” (2022), GT2022-82682 paper, Proceedings of the ASME Turbo Expo
15. Silvestri, P., Reggio, F., Niccolini Marmont Du Haut Champ, C. A., Ferrari, M. L. and Massardo, A. F., “Compressor Surge Precursors for a Turbocharger Coupled to a Pressure Vessel”, Journal of Engineering for Gas Turbines and Power 144 (11), 111014.
16. Ferrari, M.L., Pascenti, M., Abrassi, A., “Test Rig for Emulation of Turbocharged SOFC Plants”, E3S Web of Conferences, 2019, 113, 02001
17. Niccolini Marmont Du Haut Champ, C. A., Silvestri, P., Ferrari, M. L., and Massardo, A. F., “Incipient Surge Detection in Large Volume Energy Systems Based On Wigner-Ville Distribution Evaluated On Vibration Signals”, ASME. J. Eng. Gas Turbines Power, January 22, 2021