Early surge detection in a mGT plant coupled with large volumes

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Abstract. The present work features post-processing methods applied to vibro-acoustic data acquired from a T100 micro gas turbine (mGT) plant coupled with different volume interposed plenums. Such experimental campaign was conducted by relying on a test bench developed at the University of Genoa for hybrid systems emulation. Nonetheless, the obtained results can be generalized to all advanced cycles in which a mGT is coupled with further external elements which cause an increase of plant overall volume size. Since in this case a 100 kW mGT was employed, the interposed vessel was placed between heat recovery system outlet and combustor inlet, such as in common cases relevant to small size plants.
Post-processing techniques carried out on acoustic and vibrational measurements can make available innovative diagnostic tools and predictive solutions by relying on appropriate instability indicators which are defined basing only on microphone and accelerometer experimental data.
The main results presented in this work are relevant to rotating stall and incipient surge proper identification. Such investigation has been performed to increase the knowledge about such dangerous compressor working conditions; indeed, energy systems characterized by significant interposed volumes coupled with centrifugal compressors feature issues relevant to structural damaging due to surge and rotating stall.

1 Introduction

Because of financial and polluting emission matters [1], efficiency improvement [2] is still a challenging goal in the power generation research field [3,4]. As regards the gas turbines sector, it is difficult to obtain a significant improvement by further optimizing simple cycle components since current technology has practically reached its complete development [5]. Because of this, advanced cycle designs built on further supplementary components are an actual answer to obtain an additional efficiency rise [1]. Although these design adjustments must take into account specific constraints bounded by costs and sizes [6], several advanced cycles have arrived at commercial level in certain particular areas [7]. A classic case deals with micro-turbines which need to work within recuperated cycles, in order to pursue an adequate efficiency level in small dimension units [8]. Furthermore, considerable research

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activities conducted on concentrated solar power [9], micro-humid air turbine cycles [10,11], and fuel cell-based hybrid plants [12] exhibit a prospective relevance to gas turbines coupled with supplementary components. A relevant perspective to be taken into account when supplementary components are inserted in gas turbine cycles is the volume dimension augment in the region placed between the compressor outlet duct and expander inlet. Although in certain cases (e.g., recuperated cycle) the supplementary volume is only associated with the extra ducts, in some advanced arrangements (e.g., the already cited hybrid systems) this supplementary volume increase is more than two/three times the volume size of the machine itself. Although the supplementary volume does not affect steady state operation significantly, a totally dissimilar response is encountered in transitory behavior because of a slower reaction in pressurization/depressurization processes. This strongly affects system behavior making its dynamic response more complex, particularly when approaching unstable conditions. Therefore, traditional controllers industrialized by turbine manufacturers must be totally redeveloped by taking into account this particular transient operational response. For example, the standard shutdown process must be improved by executing operations (either on the fuel alimentation system or on the electrical generator) to lower angular velocity decay trend in order to mitigate surge risk, that could be caused by a slow depressurization rate (compared to standard machine response). Indeed, among all the possible risks which can be caused by the supplementary volume during transitory behavior, surge occurrence is the most critical event for the compressor and its associated components. Because of that, particular care is dedicated to designing control strategies capable of avoiding this dangerous event [13]. Because compressor characteristic curves are not always reliable in avoiding surge phenomenon [14] in all possible operating situations (e.g., in circumstances of component degradation [15]), the characterization of surge assessable detectors is required for an extensive success of advanced turbine based systems in the global energy market. Even though some authors [16,17] presented the definition of surge precursors, in this paper a new technique is exploited to perform surge analysis in large volume plants. The approach presented here relies only on accelerometer measurements, but it seems to be effective in predicting surge events. This kind of investigation is focused on the entire cycle evaluating possible specific behavior due to the additional volume [18]. Even though the diagnostic method presented in this paper is efficient for all innovative advanced gas turbines plants, the experimental campaign exploited in this work comes from a T100 micro-turbine [19]. A complete recap of state-of-the-art techniques to detect and control surge events can be found in [20].

2 Test rig, measurement system and investigated tests

In this section, the employed experimental facility is described together with the measurement system and afterwards a short presentation of the investigated tests is provided.

2.1 Test rig

The experimental results discussed in this paper were acquired on a T100 mGT plant located at the IES (Innovative Energy Systems) laboratory of the University of Genoa at Savona campus. Said micro-turbine has been connected with additional external volumes, as schematically shown in Fig. 1.

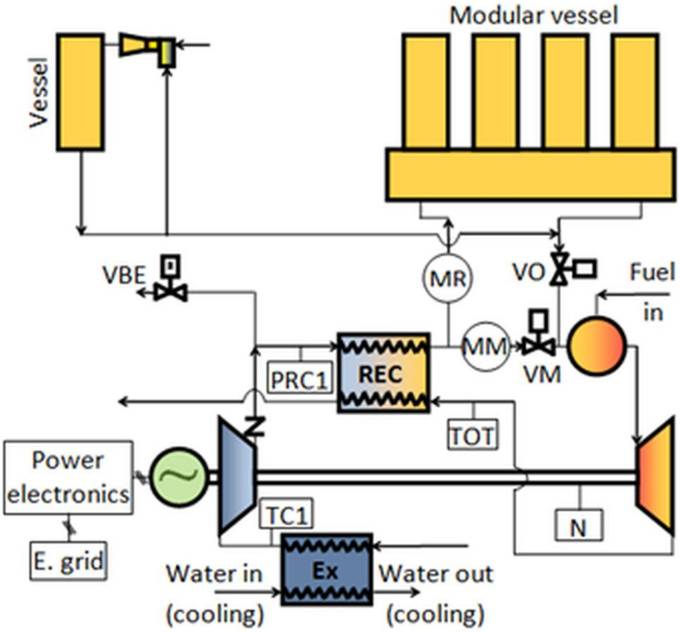

Fig. 1. Test facility configuration

The on-design main specifications of such recuperated micro gas turbine (mGT) are as follows: 100kW net electrical power, 30% electrical efficiency, 70 krpm angular speed. Since the mGT plant was modified due to the external connections, its increased volume induces large temperature (99 K) and pressure (142 mbar) drops, which make said mGT not able be operated at its on-design working point [21]. Therefore, such mGT can reach 73.5kW as maximum electrical power with compressor inlet temperature at roughly 300K and Turbine Outlet Temperature (TOT) at roughly 918.15 K. Even if said T100 mGT plant is exploited for experimental activities in this paper, such test facility had been originally thought to emulate fuel cell hybrid systems based on high temperature fuel cells. Due to this reason, external volumes consist in a modular volume plenum for the cathodic side and in a 0.8m^3 plenum for the anodic one, which also includes a recirculation system based on an ejector. The entire volume of these vessels, comprising even connecting ducts, is roughly of 4.1m^3. Said test facility is furnished with a check valve located downstream compressor outlet in order to limit damaging hazards in case of deep surge occurrence, valves which connect the turbine to the plenum volume (VM and VO) to handle the air flow path and the emergency bleed valve (VBE).

2.2 Measurement system and kind of tests investigated

The conducted experimental activity consisted in some tests where the mGT was coupled with one of the three supplementary plenum volume arrangements (i.e. the intermediate one). Said mGT was working in grid connected mode while the control system at variable angular speed was keeping the Turbine Outlet Temperature (TOT) constant at a target level (set at 918.15 K). Said mGT was started-up to a production of 40kW net electrical power, with angular speed roughly 62 krpm. Such power value was set according to different aims: remarkably off-design working conditions (mGT plants should be enough flexible in terms of part-load operating) and enough initial surge margin, while at the same time avoiding too low load functioning, in which plant control system would decrease TOT set-point; finally, it had to be a feasible beginning condition relying on the available plant components physical characteristics (e.g., VBE valve dimensions).

When a stationary plant operating condition was found, surge cycles occurrence was obtained by progressively closing the VO valve (in 2.3m^3 and 4.1m^3 cases) or the VM one (0.3m^3 case), which is located in the air path between recuperator outlet and combustor inlet. Said valves were closed by discrete steps of 10% (5% next to the surge line) until surge cycles happened, normally in a range comprised between 20 and 30% of valve fractional opening.

Structural responses were measured from accelerometers before each valve motion started, until the plant found a new stable working condition. A sample frequency of 8196 Hz was set to carry out a deep system identification both in the sub-synchronous frequency range and revolution frequency component (i.e., 1X order) together with its more significant harmonics in terms of signal energy; indeed, when emulating transient operation towards system unstable behavior, angular speed was comprised between 62 and 65 krpm, equivalent to 1033-1083 Hz. A higher sample frequency up to roughly 200 kHz was set for one micro accelerometer in order to observe spectral contents evolution around compressor blade passage frequency (about 26 kHz). Indeed, compressor impeller features 13 blades, plus 13 additional splitter ones, while turbine is only equipped with 13 main blades [22,23]. When the plant reached an unstable working condition, just few surge cycles could be acquired, since mGT control system immediately shut down the compressor to limit damage risks. Indeed, mGT plant is equipped with an industrial diagnostic system, based only on an industrial accelerometer; therefore, if a threshold vibration level is detected, an instantaneous shutdown is started to protect plant components [21]. Therefore, the industrial control system already implemented for surge detection is not effective in identifying incipient surge but only in capturing a fault condition when it has already developed. To this goal, compressor transient operations are investigated to look for variations in its structural responses between stable and unstable functioning; indeed, a change in structural response signals spectral pattern is expected that gives information about turbomachinery operating conditions which can be exploited for diagnostics and anti-surge control systems based on not intrusive probes. In particular, in this case system structural response signals acquired by different accelerometers were acquired; the exploited sensors are a mono-axial accelerometer mounted on rolling bearings housing located in axial direction (ICP accelerometer characterized by nominal sensitivity 10 mV/g) and a high-frequency mono-axial accelerometer placed on compressor housing in radial direction (piezo-electric in-charge accelerometer characterized by nominal sensitivity 3 pC/g and appropriate for measurements up to 250 °C) [21].

In this paper the aim is to identify the nature of physical phenomena which happen when passing from incipient surge conditions to surge and in general when the plant moves towards instability, starting from stable working conditions. Such approach also allows to investigate system operating response just before the first deep surge cycle occurrence (i.e., in incipient surge conditions), in order to detect an energy increase in some frequency components which may identify rotating stall cells inception. As in [24] and differently from the experimental activity performed in [21], that focused only on the last stable operating points just before surge onset, the present work focuses on structural response signals recorded on the compressor when it undergoes surge instability (reference surge transient starting from incipient surge to surge cycles); afterwards, the so acquired response signals were investigated and their results compared with the ones obtained from signals recorded in stable working conditions, far from low mass flow rate instabilities, namely surge and rotating stall.

3 Results and discussion

In this section, results obtained by relying on the previously described test rig and measurement system are discussed in detail.

3.1 Vibro-acoustic signature analysis in stable conditions

In the present subsection, vibro-acoustic system signature has been investigated by means of a run-up test, where angular speed was increasing according to a linear ramp; the adopted constant acceleration allowed to explore the whole mGT operational range in order to identify system mechanical resonances. Indeed, the main goal is to characterize system structural behavior in “stable” conditions, meaning far from low mass flow rate instabilities.

A time-frequency colormap obtained basing on Short Time Fourier Transform (STFT) is reported in Fig. 2; in such representation the abscissa axis stands for frequency, whereas the ordinate axis reports system angular speed. In this way, engine orders are identified by lines at constant slope. Finally the third axis stands for signal energy, in this case related to vibrations magnitude. 1X order (that is, revolution frequency) together with its second integer multiple (2X order) are represented to look for mechanical resonances; indeed, if an increase in signal energy is found along the lines relevant to an engine order show, then a likely mechanical resonance is identified. In particular, being 1X order the fundamental harmonic of the excitation (i.e. angular speed) system structural response should be amplified when a mechanical resonance is found. Indeed, in this case, an energy increase in 1X order is detected at around 542Hz which may be due to a mechanical resonance of some system components. Such resonance is well identifiable even looking at 2X order, which shows a significant energy increase in correspondence with 1104Hz, which is roughly the double of 542Hz. Indeed, in this case, the mechanical resonance is well identified even by the first harmonic of 1X order, thus further confirming that the system exhibits a natural frequency at a fundamental frequency at 542Hz, whose energy is significant even in its second harmonic component.

Finally, in the sub-synchronous frequency range structural response signal energy does not exhibit significant frequency components; indeed, spectral contents equivalent to fractional engine orders (less than 1X order) are not characterized by remarkable amplitude in the examined working conditions, regarded as baseline configuration for surge diagnostics.

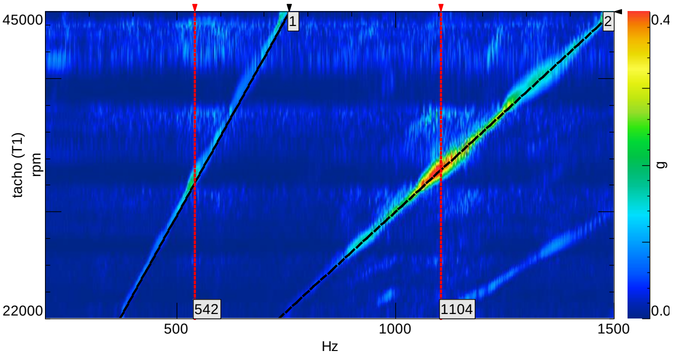

Fig. 2. Time-frequency analysis (STFT) of structural response signal in ramp-up conditions

3.2 Surge transient analysis

In the present section the reference surge transient is investigated in detail. A time-frequency analysis (STFT) is performed on structural response signal in the sub-synchronous frequency range. With respect to vibrational signature analysis conducted in stable behavior, far from low mass flow rate instability, some spectral contents can be identified which increase their energy when moving towards surge.

Indeed, a variation in structural response signal spectral pattern can be clearly identified: the energy of some frequency components significantly increases with respect to system structural behavior previously observed in stable conditions, far from the surge line. In particular, the sub-synchronous range is investigated since it is the more likely frequency interval where rotating stall cells energy can be detected when approaching surge [25-26].

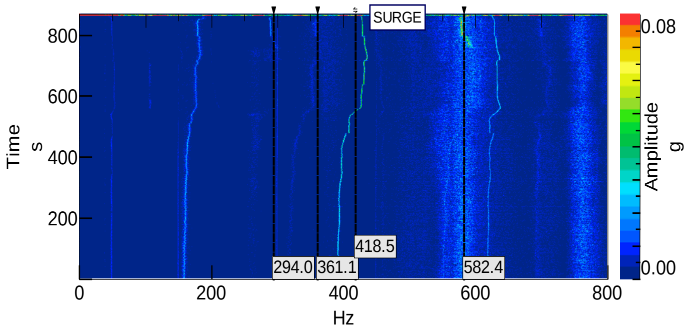

Fig 3. Time-frequency analysis (STFT) of structural signal in surge transient - sub-synchronous range

In particular, two spectral contents can be identified at roughly 294Hz and 361 Hz which increase their energy in incipient surge conditions. Moreover, a spectral content can be detected which is characterized by a characteristic frequency variable during the reference surge transient, which stabilizes at about 419Hz just before surge inception. It may be ascribable to rotating stells onset within the compressor which can induce a structural response characterized by significant energy in correspondence with the characteristic frequency of this fluid-dynamic instability; indeed, rotating stall can occur before surge onset and the increase of signal energy in structural response in the sub-synchronous frequency range may be regarded as a reliable anti-surge diagnostic indicator [27-28].

4 Conclusions

The main goal of the conducted investigation is to prove the effectiveness of time-frequency analysis for incipient surge detection by relying only on system structural response signals. To this aim, suitable surge transients were obtained and afterwards STFT was carried out on appropriate time extracts selected from the acquired transients. By doing so, frequency components energy trend can be observed to assess how it evolve with time when approaching surge starting from a nearly unstable condition (i.e., incipient surge).

The presented investigation was caried out on a modular mGT plant where compressor discharge volume can be tuned in order to emulate mGT real plant configurations; by doing so, time-frequency analysis effectiveness in detecting system working conditions change due to an incipient low mass flow rate fluid-dynamic instability was assessed. Said signal processing technique allowed to perform a detailed system identification by detecting well identifiable spectral contents pattern variations according to system current working point.

In detail, an energy variation in the spectral pattern of system structural response is observed in the sub-synchronous range when passing from stable to unstable operating conditions. Similar results can be obtained even considering acoustic system response, which can be exploited jointly with structural one to define suitable surge precursors by relying on vibro-acoustic response signals energy in the sub-synchronous frequency range.

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