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A statistical approach to the analysis of the surge phenomenon

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The paper presents an innovative data processing methodology for the analysis of the surge phenomenon occurring in a compressor. Since the dynamic of the surge cycle does not have a deterministic character, its proper description can only be obtained through a statistical approach. To this aim, the temporally resolved traces of the pressure and mass flow rate signals are processed through a phase averaged decomposition technique. Furthermore, the shape of the oscillating surge cycle is detected and quantified by introducing the joint probability density function of the aforementioned signals which are reported in the pressure ratio versus mass flow rate plane. This probabilistic approach offers two significant advantages over the conventional deterministic approach, namely the possibility to quantify the time of residence of all individual unstable states in a statistical sense, as well as the possibility to carry out a proper code-to-experiments or experiments-to-experiments comparison of such an unstable phenomenon.

In this paper, the proposed statistical approach is used to process the experimental data related to the surge phenomenon occurring in a small-sized free spool centrifugal compressor for automotive applications. However, the methodology can be applied both to numerical and experimental surge data from either centrifugal or axial compressors.

1. Introduction

Nowadays, the reduction of the engine displacement is one of the most widespread and successful technique used to reduce the fuel consumption and the pollutant emissions of internal combustion engines (ICE). However, in order to preserve or even augment the delivered power, the ICE has to be charged, for example through a turbocharger (TC) [1–5]. In such a way the intake air density, the mass flow rate and consequently the power output are raised while retaining a small engine size. Further combustion advantages can be gained by turbocharging the ICE, such as an improved fuel atomization process [6] and a shorter fuel jet penetration length [7]. In spite of the aforementioned benefits, some drawbacks also exist. First of all, there are a few well-known shortcomings associated to the poor quality of the transient response of turbocharged engines [8–11]. These problems are mainly associated to the mechanical inertia of the TC which induces significant delays in the charging effect during those maneuvers requiring a rapid increase of the delivered power. Another drawback can be caused by the occurrence of the critical surge phenomenon. Operating the compressor in surge regimes is not at all recommendable since it induces a significant drop down in the compressor efficiency, a probable failure of the TC mechanical components, undesirable noise, and, finally, a reduction of the vehicle driveability due to the oscillating power output. From the previous considerations, it is clearly understood that a proper characterization of the TC operating in the unstable surge regime is very important. This is witnessed by the large amount of research papers dealing with this issue. For instance, in Ref. [12] the authors described a test bench specifically designed for the characterisation of automotive TCs and used it to define a sound criterion for the surge limit definition. An experimental investigation of the effects of an inlet swirl generator to enlarge the surge margin is reported in Ref. [13]. Galindo et al. [14] developed a surge model in which the fluid inertia effects are taken into account. The model is validated against data measured in a specifically designed facility. Andersen et al. [15] proposed a standardized measurement setup for the definition of the compressor surge limit. The effects of a pulsating flow at the compressor outlet are analysed in Ref. [16] by experimental means. Specifically, the effects of the amplitude and frequency of the pressure oscillations upon the surge line have been described. The authors found that, for the typical frequencies

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Nomenclature

f	frequency
f_0	fundamental frequency
f_s	sampling frequency
$\dot{m}$	mass flow rate
$\overline{\dot{m}}$	long time averaged mass flow rate
N	rotational speed
N_c	number of surge cycle
$N_{\Delta S}$	number of samples falling in a grid cell
N_s	total number of samples
$N_{s,T}$	number of samples in a surge cycle
p	static pressure
$p_{\dot{m},\pi}$	probability density function
Pr	probability
S	subset of the plane $(\dot{m},\pi)$
T	period of a surge cycle

Greek symbols

π	pressure ratio
$\overline{\pi}$	long time averaged pressure ratio
ϕ	generic quantity
$\langle\phi\rangle$	phase averaged quantity
$\tilde{\phi}$	modulation
$\overline{\phi}$	long time averaged quantity
ϕ'	perturbation
ΔS	area of the grid cell

Subscripts

D	delivery
ref	reference quantity
S	suction

Acronyms

BST	best straight line
CC	centrifugal compressor
FFT	fast Fourier transform
FS	full scale
FSO	full scale output
ICE	internal combustion engine
PDF	probability density function
TC	turbocharger

characterising the pulsating flow in turbocharged engines, a surge margin enhancement is possible. Guillou et al. [17] carried out PIV measurements in the proximity of the centrifugal compressor (CC) inlet, both in stable and unstable regimes. In Ref. [18] a properly designed test bench is used to point out the dependence of the surge margin from the piping configuration upstream and downstream a CC. Finally, the design and prototyping of a new highly flexible hot gas generation system is reported in Ref. [19], while in Ref. [20] the collected experimental data are manipulated to estimate the effect of the thermal losses on the compressor efficiency, and to analyse the surge phenomenon.

As proven by the above literature review, up to now the surge phenomenon has always been studied through a deterministic approach based on the single cycle characterisation. Conversely, in this paper a new and more advanced data processing methodology is proposed. In more detail, based on the fact that the surge cycle is not deterministic in nature, the analysis is conducted through an original statistical approach relying on the processing of the temporally resolved traces of the pressure and mass flow rate signals. The statistical description of the phenomenon is two-fold. Firstly, a spectral analysis of the collected signals is carried out in order to build the phase locked averaged quantities offering the appealing opportunity to properly characterise the intrinsic surge unsteadiness. Secondly, the shape of the oscillating surge cycles set is detected and quantified by introducing the joint probability density function of the aforementioned signals which are reported in the pressure ratio (π) versus mass flow rate ($\dot{m}$) plane. This statistical approach, which as far as we are aware has never been proposed before, allows to quantify the time of residence of all individual unstable states, an information of the utmost importance for the evaluation of the global aerodynamic loads affecting the rotor dynamics. It further offers the possibility to compare, in a quantitative fashion, calculations with experiments and/or experiments with experiments, a task that can not be properly accomplished using a conventional deterministic approach based on the single cycle characterisation. In fact, because of the intrinsic chaotic nature of the surge phenomenon, measurements based on a single cycle (or few cycles) realization do not allow to properly validate surge models. Similar drawbacks arise when comparing results of different experimental campaigns using a conventional deterministic approach. Instead, processing the data with statistical tools, like the phase-average technique and the joint probability density function, offers the possibility to take advantage of the information buried in a large number of surge cycles, each of which has stochastic character. By so doing, a more reliable representation of this complex phenomenon is attained. Therefore, new or existing surge models are more exhaustively validated through the phase-averaged surge cycle and the associated probability density function. The same is true if the results of different experimental campaigns have to be compared.

In this paper, the proposed processing strategy is applied to study the surge phenomenon in a small-sized free spool CC for automotive applications. The study is carried out by a specifically designed test bench, described in section 2, which has been equipped with fast response pressure and mass flow rate sensors. Then, the main features of the surge phenomenon are studied by phase-locked averaging the collected signals (see §3.1) and by inspecting their joint probability density function in the $(\dot{m},\pi)$ plane (see §3.2). Note that, although the proposed methodology has been applied to the experimental study of the surge in a small-sized CC for automotive applications, it can be generally applied to both axial and radial compressors and to experimental and numerical results.

2. Experimental apparatus

Fig. 1 shows a schematic view of the experimental apparatus employed to characterize the unsteady behaviour of the tested turbocharger.

As shown in this figure, the mass flow delivered by the centrifugal compressor is discharged at ambiance through a back-pressure valve which is remotely operated to span the whole characteristic map in a semi-automated manner. The CC is driven by a centripetal turbine which is fed by a hot gas generator consisting of a 2.5 l diesel engine. A Borghi&Saveri FE 350SA eddy current dynamometer is used to operate the engine both in steady and variable *rpm* regimes. In order to properly span the compressor map, the total amount of exhaust gas is directly sent to the test