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Methods of surge point judgment for compressor experiments

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ABSTRACT

Precise judgment of surge point is crucial for compressor performance experiments. Three types of dynamic measurements (pressure, temperature and acoustic noise) have been investigated to judge the surge points of compressor. Fast-response pressure and temperature probes are mounted at the impeller inlet and diffuser mid-section while microphones are set up in vicinity of the casing and duct inlet of a centrifugal compressor. Thus, typical forms of surge and signal features from different measuring tools are minutely discussed; some analysis are presented and connected with predecessors' researches on flow mechanism of stall or surge. Finally, an efficient criterion for surge point judgment has been concluded that the standard deviation of temperature signals have an abrupt rise-turn at the minimum flow rate limit. This new criterion has been verified in different types of centrifugal compressors, which can help judge surge point of compressors' performance map in a relatively accurate and quantitative way.

1. Introduction

Surge is one of instability phenomena when a compressor operates in small flow rate at the constant speed or a given pressure ratio. The amplitude of several thermodynamic or aerodynamic parameters will drastically oscillate, such as pressure, temperature, noise when surge occurring [1], which will immensely violate safety, durability and reliability of the turbomachinery even the power system. Meanwhile, the surge line represents the minimal operation boundary of the compressor, which evaluates the performance of the compressor. So it is essential to accurately determine the surge points for an e compressor map that scaling performance and operation stability of the compressor.

In traditional experiment for performance, the surge point is determined by the aerodynamic noise of compressor. A distinct cyclic noise akin to a "sewing machine whistle" can be heard at the onset of instability operating conditions in the compressor [2]. However, this subjective method relies on the operators' experience and environment conditions, which may arbitrarily induce different experimental results. Especially, surge at low pressure ratio is a gradual process of transformation as flow rate is reducing [3]. So it merits to establishing objective criteria to judge the surge points.

Commonly, dynamic signal methods have been utilized to seize the transient features of compressor surge. Galindo et al. [4] monitored air mass flow, inlet temperature and outlet pressure to detect surge by observing instability signals in time domain graph. The same research group also used Fourier analysis to the dynamic quantities and discover enormous amplitude rise at low frequency when surge occurs [5]. On the other hand, microphones inside the gas path have been used to correlate the vibroacoustic signal of the instability operating conditions [6]. These literatures delineate the violent perturbation of dynamic quantities, for instance, an abrupt spike in operating signals [7], which helps accurately determine the surge. However, both spike type and modal type have been observed in literatures [8–10], while the second type is much less evident so that some quantitative indexes with data processed should be raised.

Zhu et al. [11] calculate mean square deviation of outlet pressure as the key parameter of operation and determine the critical value of surge. Aretakis et al. [12] use fast hot-wire anemometers, microphones and acceleration sensors to perform compressor instabilities, while acoustic signals are filtered and extracted to establish a parameter, in comparison with a critical value to illustrate whether it comes into surge operation. However, the correlation between instability flow features and dynamic instruments' signals, as well as the differences among various instruments is barely specified. So, it is uncertain about the best instruments for surge point judgment.

There is a consensus that flow turbulence and separation grow into finite stall cells prior to and during the microscopic instability surge [8,10,13–22]. So, more investigators concern about detection of stall inception of compressors, and more successful cases are investigated in axial compressors [8,14,15,20,21]. Fast-respond pressure probes and hot-wire anemometers are mounted at different cross-sections along stream passage of the axial compressor rotor so that pressure and velocity data are analyzed when

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Nomenclature

a	averaged sound velocity	SD	standard deviation
Ac	equivalent cross-sectional compressor duct area	T1	static temperature at the impeller inlet
DC	direct-currency	T2	static temperature near diffuser exit
fH	surge Helmholtz frequency	PSD	power spectral density
lc	equivalent length of the duct	Vp	volume of the compressed air
P1	static pressure at the impeller inlet	ϕ	corresponding physical quantity
P2	static pressure near diffuser exit	ωs	speed of rotation stall
S1	sound pressure to the casing of the compressor	Ω	rotation speed of the impeller
S2	sound pressure at the inlet of the intake duct		

compressors gradually come into stall. Several investigators utilize post-processing algorithms [14], for instance, simple visual inspection of time serial, discrete spatial Fourier serials (DSFS) analysis, traveling wave energy (TWE) analysis, wavelet analysis and spatial correlation metric (SCM), have been developed to seek the precursors of instability surge. Even several effective active surge-control strategies based on surge or stall inception have been achieved [15]. Flow phenomenon in centrifugal compressor is more complex than that in axial one, so dynamic pressure and velocity measurement are tentatively utilized in centrifugal compressors. For example, transducers are always equally allocated around the circumference of the impeller and diffuser of low-speed centrifugal compressor [11,15,17]. These literatures primarily research on flow mechanics of surge and stall, and achieve various perspectives to explain it and methods to capture stall inception.

However, when it comes to high-speed centrifugal compressor (above 100,000 r/min), similar researches are quite absent, for the first reason that high-speed centrifugal compressor means compact structure and it is extremely intractable to furnish abundant probes on the same cross-section. Secondly, in order to abate intrusive influence on the actual performance of the compressor, as well as inconvenience of installation in the aspect of engineering, fast-response probes set up to seize surge features should be as few as possible. Hence, none of complex post-processing algorithms, based on relation of measuring data at various positions, can be applied. What is more, high-speed centrifugal compressors imply high pressure ratio and more turbulent aerodynamic characteristics, which maybe a distress to illustrate the rotating stall or surge inception features by some of the methods above. Therefore, a small number of transducers will be employed to concern about slightly macroscopic dynamic information other than aerodynamic details. Likewise, the post-processing method should be relatively direct and concise.

As mentioned above, flow is more complex and the surge is demonstrated in diverse forms at high-speed centrifugal compressors. So, in this literature, different dynamic instruments will be utilized to grasp dynamic signal of different operations in s high-speed centrifugal compressor. Then, signal features will be interrelated with surge occurrence and respectively compared. Finally, an efficiency concise criterion will be introduced and verified to determine the surge points.

2. Experiment design and experimental facilities

2.1. Experiment design

The experiment is grounded on a high-speed centrifugal compressor turbocharger. The specifications of the experimental compressor are shown in Table 1.

The schematic diagram of the rig test facility is shown in Fig. 1. Pressurized air is heated by a combustion chamber in front of the turbine and then expanded in the turbine to drive the compressor at a specified rotational speed. Leminiscate flow meters are placed at the inlet duct, remote from impeller inlet. Low-respond probes are placed at sections C1 and C2 to measure total/static pressure and temperature at both the inlet and outlet of the compressor. Meanwhile, rotation speed and ambient pressure and temperature are also obtained. All of these steady data above are required to make sure the operation points and the whole map of the compressor.

Table 1
Specifications of the experimental compressor.

Parameter	Value
Impeller exit diameter	60.0 mm
Impeller inlet diameter	35.8 mm
No. of impeller blades	12
Diffuser type	Vaneless diffuser
Diffuser ratio	2.4
Max speed	185,000 r/min
Pressure ratio	4.8

The aim of the study is to establish the surge criteria that can be adopted in actual operation of the compressor. So the diagnosis methods must be engineering approaches. The pressure signal oscillates the most prominently so that it is always used to analyze the rotation stall and judge the surge inception [12–22].

Temperature fluctuation has some relevance with that of pressure because of the air's thermal physical property. However, temperature measured lags behind pressure for high-response thermocouple and pressure probe base on different measuring theories. The hot end of thermocouple generates electromotive force toward the cold end when heat flux conducts to the hot end. Thermal conductivity of air and metal section will postpone the heat perception at the hot end. The thermocouple responds slower than pressure probe while it can monitor low frequency fluctuation of the surge flow.

Aerodynamic and vibration noise is the empirical surge-judging criterion. Aretakis et al. [12] establish a quantitative criterion by vibroacoustic measurements. This study expects the pre-surge

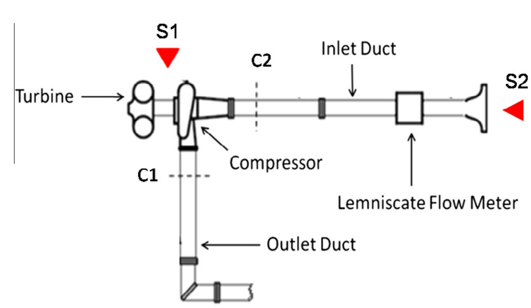

Fig. 1. Schematic diagram of the rig test facility.