Aerospace Science and Technology 80 (2018) 144–155

Contents lists available at ScienceDirect

Aerospace Science and Technology

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# Numerical investigations on stator hub initiated stall in a single-stage transonic axial compressor

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ARTICLE INFO

*Article history:*
Received 2 February 2018
Received in revised form 9 May 2018
Accepted 10 July 2018
Available online 18 July 2018

*Keywords:*
Transonic axial compressor
Flow instability
Stall inception
Partial surge
Rotating stall

ABSTRACT

A new kind of stall inception initiated from the stator hub region was recently identified by experiment in a transonic compressor. To further explore the mechanisms of the new stall inception, the detailed stall evolution is studied in this paper using full-annulus unsteady simulations. The simulations correctly predict several key characteristics observed in the previous experiments: (1) the stall precursor is initiated in the stator hub region; (2) the initial disturbance is axisymmetric; (3) asymmetric rotating disturbance is developed afterwards. The numerical results also illustrate that the stall evolution has two distinct phases: the part span stall and the global stall, which are associated with the axisymmetric and the asymmetric disturbances respectively. The axisymmetric disturbance is caused by the ring-shaped flow separation in the stator hub region, while the asymmetric disturbance is initiated by the breakdown of the symmetry of the ring-shaped separation. For both disturbances, the axial velocity waveforms are in anti-phase at the stator tip and hub region, so they have the 1st-order mode in the span-wise direction. Further discussions on the radial distribution of load indicate that the localized critical load is the key factor leading to the earlier occurrence of flow breakdown in the stator hub region.

## 1. Introduction

Rotating stall of compressor has drawn special attention since the first observation in aero-engines in the 1940s because it usually leads to flow instability and mechanical failure [1]. Earlier studies focused on the description of this phenomenon. Later, Sears [2] and Emmons et al. [3] modeled the rotating stall in a 2D cascade row. Takata et al. [4] constructed a nonlinear model to predict the characteristics of stall cell. In 1976, Greitzer [5,6] proposed the "B parameter" model to estimate the response of a compression system to predict the occurrence of surge or rotating stall under a given condition. These studies prepared for the discovery of rotating stall inceptions.

Two typical types of stall inception have been well known. In 1986, Moore and Greitzer [7,8] theoretically predicted the existence of a small-amplitude disturbance with large length scale in axial compressors, which is now called modal wave. Later on, modal wave was experimentally identified by McDougall et al. [9], whose results also verified the concept of "M-G model", which says that modal wave is caused by the circumferential asymmetry. In 1993, Day [10] discovered a different type of stall inception in his experiments and called it "spike", which was characterized by nonlinearity, small length scale and large amplitude. Spike was also reported later in different compressors by Park et al. [11] and Hah et al. [12].

Modal wave generally initiates at the full span, while spike initiates in the rotor tip region; different from them both, other stall inceptions initiated in the hub region have also been found in recent years. Dodds et al. [13,14], Dell'Era et al. [15], and Li et al. [16–18] observed stall phenomena initiated in the hub region in different compressors. The new type of stall inception observed in the experiments of Li et al. was called "partial surge", which is a low-frequency, axisymmetric disturbance initiated in the hub region. This type of partial-surge inception has features different from those of modal wave and spike.

With the development of high-performance computing, CFD methods have been extensively used to simulate the evolution of compressor stall and to study the mechanisms of different types of stall inception. Dodds et al. [14] and Gourdain et al. [19] demonstrated the capability of numerical simulation in predicting the rotating stall phenomena using the URANS method. Khaleghi [20] and Chen et al. [21] illustrated that the tip clearance flow played

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https://doi.org/10.1016/j.ast.2018.07.018
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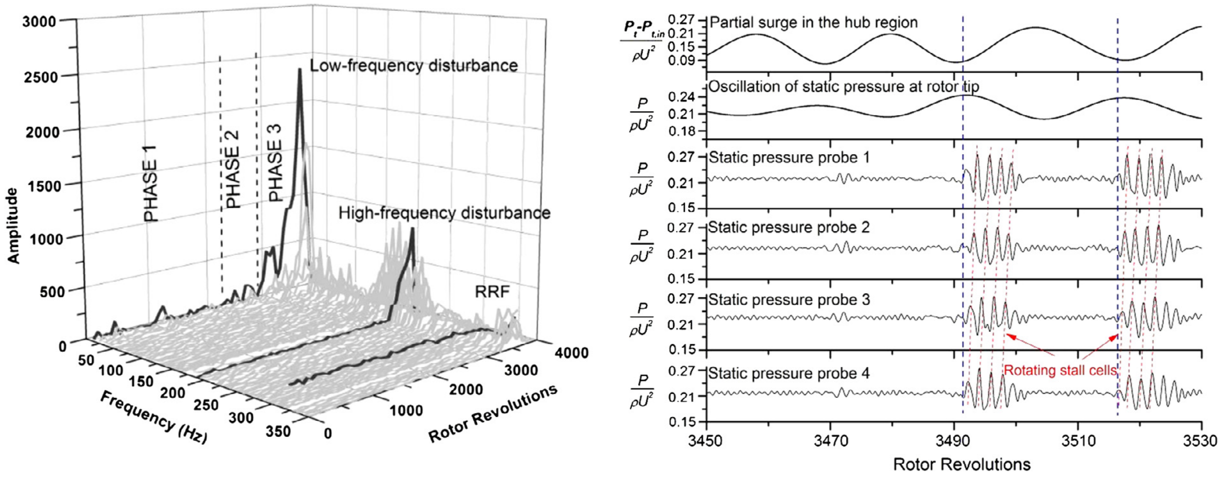

(a) FFT of temporal signals

(b) low and high frequecy disturbances

**Fig. 1.** Total pressure in the rotor tip region, from experimental results by Li et al. [16].

a leading role in the spike-type breakdown through full-annulus simulations. Vagnoli et al. [22] numerically studied the influence of inlet distortions on a modal-type stall inception. In general, CFD methods have provided an efficient tool for studying the stall mechanisms in compressors.

The basic features of partial-surge stall inception were identified from experimentally collected transient stall signals [16–18], but limited by the measurement instruments, the detailed mechanisms for the formation and propagation of stall disturbances still remain unknown. Therefore, in this paper 3D full-annulus unsteady simulations are conducted to compute the evolution of stall in the same compressor used in the aforementioned experiments, with the aim of predicting and exploring the underlying mechanisms for the development of partial-surge stall inception.

The main content is organized as follows: first, a brief review of the stall evolution observed in the experiments of previous studies is presented in Sec. 2, which leads to the motivations and objectives of this study. Next, the modeling details and methods used in the simulations are presented in Sec. 3. Then, the simulation results and corresponding explanations are presented in Sec. 4, which is followed by several general discussions about the deficiency of the current simulations and the conditions for the occurrence of stator hub initiated stall (Sec. 5). At last, conclusions are drawn in Sec. 6.

## 2. Motivations and objectives

Compared with spike and modal wave, partial surge has displayed very different behaviors in the previous experiments. Fig. 1a shows two disturbances during the development of stall: the “low-frequency” and “high-frequency” disturbance. The low-frequency disturbance is considered as the stall inception because it occurs earlier and has larger amplitude, and the high-frequency disturbance is generated right before the final stall. The low-frequency disturbance is the 0-th order axisymmetric oscillation (so called “partial surge”), and the high-frequency disturbance is the 1st-order rotating stall cell, as shown in Fig. 1b. The high-frequency disturbance is induced by the low-frequency one because it always emerges after the wave trough of the latter and disappears before the wave crest. The evolution of stall lasts over 3000 revolutions prior to the final compressor instability.

A comparison of the evolution of total pressure at the stator and static pressure in the rotor tip region is shown in Fig. 2. The low-frequency disturbance initiated in the stator hub region has the largest amplitude. Besides, the waveforms in the stator hub and tip region are in anti-phase.

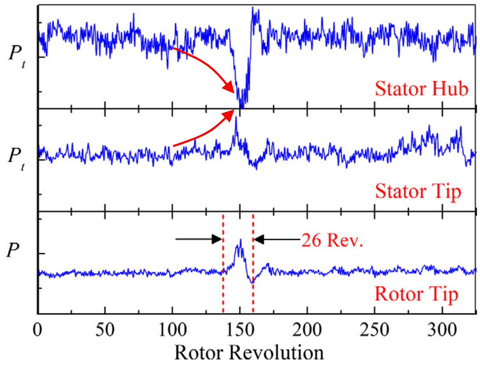

**Fig. 2.** Initial position of the low-frequency disturbance, from experimental results by Pan et al. [18].

In sum, partial surge mainly has three features: (1) the stall inception is initiated in the stator hub region; (2) the initial disturbance is a low-frequency axisymmetric disturbance; (3) a high-frequency rotating disturbance is developed afterwards.

Because of the limitations of measurement capability, many details are still unknown about this type of stall evolution, such as the origins of the two disturbances, the development of disturbances inside the compressor, and the conditions resulting in the premature occurrence of flow breakdown at the stator hub. To answer these questions, flow field observations and Fourier analyses of the disturbance waves based on 3D full-annulus unsteady simulations are conducted in this study.

## 3. Modeling and methodology

### 3.1. Simulated compressor

The axial transonic compressor tested in reference [16] is simulated, in which partial surge was observed. Its design parameters are listed in Table 1. The rotor has 17 blades with a relative tip clearance of 0.77% with respect to the blade height, and the stator is a tandem row with 29 blades for each row. The studied rotor speed is 88% (19360 rpm) of the design speed. The inlet relative Mach number at the rotor tip is about 1.4. The stator hub region is critically-loaded where the diffusion factor exceeds 0.5 at the design point.