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The stall inceptions in an axial compressor with single circumferential groove casing treatment at different axial locations

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ABSTRACT

Circumferential groove (CG) casing treatment is known to be a good method to improve the stall margin of axial compressor. Recent studies on single groove indicate the stall margin improvement (SMI) is significantly affected by groove's axial location, which means the effects of the groove on the passage flow should be further studied as the groove's axial location is changed. In this paper the features of stall inception with and without the groove treatment are experimentally researched in a low-speed axial compressor. The contour of static pressure on casing is obtained by fast-response pressure transducers concentrative mounted as a line in chordwise direction, and the data acquired by transducers in circumferential direction is processed with the method of wavelet analysis to demonstrate the development of stall inception. It is found the stall inception is the typically spike-type for smooth casing (without treatment), which is manifested as short-scaled disturbance of only 2–4 blade passages when it appears. Two single grooves at different axial locations, which can be ineffective and effective in SMI, are further tested. The results indicate the stall inception is still spike-type for both of them. However, for the ineffective groove, the stall inception is found to be relatively longer-scaled disturbance. For the effective groove, it is still the typical short-scaled disturbance similar to the smooth casing. In the further study on double grooves treatment in which the ineffective groove is included, the stall inception is also found to be relatively longer-scaled type. According to these experimental results and previous CFD simulation, the groove with almost no SMI is believed to take different effects on the compressor which modifies the stall inception into the relatively longer-scaled type, and the corresponding tip–region flow structure deserves more future study in this regard.

1. Introduction

Sufficient stall margin is crucial to the safe operation of axial compressors. Many researches have been focusing on the methods to improve the stall margin, among which the circumferential groove casing treatment is proved to be a simple and effective method. In previous literatures, much attention has paid to on understanding the mechanism by which the grooves improve the stall margin. It is generally believed the "suction–injection" effect exists on the two sides of blade due to the groove treatment (Shabbir et al. [1]). In this regard, the change of tip leakage vortex trajectory by grooves is widely discussed, such as the researches Müller et al. [2,3] and Bennington [4]. The tip leakage flow (TLF) is deflected and the spillage of the interface between tip leakage flow and main flow is then postponed by this effect (Nan et al. [5]), which is deemed as the criteria for the appearance of spike-type stall inception proposed by Vo et al. [6].

In recent years, the single groove has also been widely investigated as it is a direct method to clarify the groove's mechanism at different axial locations, such as Sakuma et al. [7] and Houghton et al. [8]. In the experimental researches, the interesting two peaks of SMI when the groove's axial location is changed are revealed, as shown in [8], while the groove locates between the two peaks generates almost no SMI. This phenomenon is difficult to be explained with the common view that the groove near the leading edge generates higher SMI as the spillage of TLF is postponed more effectively [1,3]. Furthermore, it also implies the effects of single groove on the passage flow may be different as its axial location is changed, especially for the groove located between the two peaks of SMI. In order to better reveal the grooves mechanism, the phenomenon of the two SMI peaks should be further studied, which is the initial motivation of this paper.

As for the SMI of groove treatment, it has been mentioned that it is attributed to the delay of TLF spillage. In most modern com-

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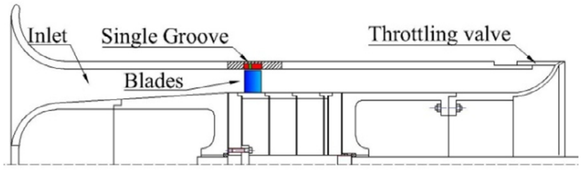
pressors, this spillage is observed in blade tip region which leads to the spike-type stall inception (Vo et al. [6], Ann Review [9]). As a common point of view, the spike-type stall inception is the short-scaled disturbance with relatively high propagation speed when compared with the modal type, which was summarized by Day [10]. On the other hand, Wyer et al. [11] found that the groove treatment has no effect on the stability for the highly hub-loaded compressor. These literatures indicate the effects of groove treatment most probably focus on tip region flow. Furthermore, if the two SMI peaks found in single groove tests are considered, whether the grooves at various axial locations correspond to different effects on tip–region flow becomes an interesting issue worthy of study. In fact, Du et al. [12] already discussed the stall inception with the single groove treatment by numerical simulations, in which it was concluded the stall inception is relatively long-scaled for the groove locating between the two peaks of SMI but generating no SMI. In this regard, the change of stall inception caused by single groove is a meaningful topic, which will be further discussed in this paper.

Based on this background, the main goal of this paper is to discuss the impacts of single groove treatment on stall inception. As a fundamental research, the change of flow features in blade tip region by single groove will be studied in detail rather than designing a casing treatment with higher SMI. According to the interesting SMI trend of single groove found in previous researches, two typical axial locations are selected for the tests in a low-speed axial compressor: one groove is located between the two peaks of SMI but is ineffective in SMI, while the other groove generates quite high SMI which is located near the second peak of SMI. The fast-response pressure transducers are mounted on casing in both the chordwise and circumferential direction in order to capture the appearance and development of stall inception. The appearance of stall inception is demonstrated with the contour of the static pressure on casing, and its development is further studied by wavelet analysis. Based on these experimental results, the scale and development of stall inception with and without single groove treatment are compared. Besides, as the further study for the single groove with almost no SMI, the design of double grooves treatment containing this groove is also tested to confirm its effects on stall inception. In the last section, the possible tip–region flow structure which leads to the change of stall inception is discussed based on both the experimental results in this paper and previous CFD simulation.

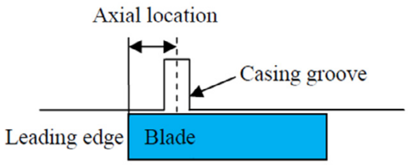
2. Experimental set-up

A low-speed axial compressor is used for the experiments in this paper, which is an in-house compressor for fundamental research associated with compressor stall. The blades are designed based on one stage of a high-pressure compressor. As the research in this paper is focused on the change of stall inception caused by single groove and the corresponding flow features in blade tip–region, the IGV and stators are not included, which means a single rotor structure in the experiments. The structure of the test-rig is shown in Fig. 1(a), and Fig. 1(b) is the detailed illustration for groove treatment. The parameters of the tested compressor are listed in Table 1.

In the experiments, the compressor is gradually throttled by step motor until the occurrence of stall. During this process, the steady measurements are continuously performed for the calculation of characteristic curve.



(a) The Structure of the Test-Rig



(b) The Groove Treatment

Fig. 1. Illustration for the test-rig and groove treatment.

Table 1
Parameters of the tested compressor.

Design flow rate (kg/s)	3.2
Design rotating speed (rpm)	2400
Number of blades	60
Casing diameter (mm)	500
Blade tip chord (mm)	36.3
Tip clearance (mm)	0.70
Aspect ratio	1.74
Hub to tip ratio	0.75
Tip stagger angle (°)	39

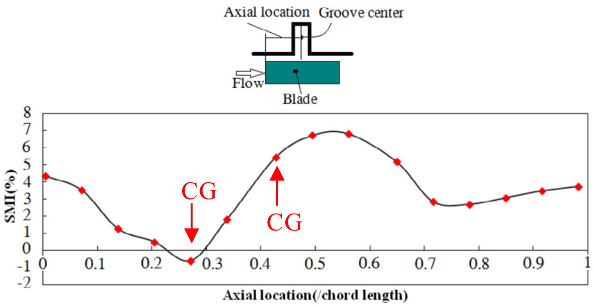


Fig. 2. SMI trend with single groove's axial location [13].

In this test-rig, Li et al. [13] have already studied the single groove with the width of 3 mm and depth of 6 mm. In their research the axial location of the groove was varied from 0.4% to 98.3% C_a (C_a is the axial chord length), and two peaks of SMI were found in these tests, as shown in Fig. 2. Based on this research, the single groove with the same geometry will still be tested in this paper. The groove's naming is also the same with literature [13]. According to the SMI trend, two typical locations are selected for the study in this paper. One groove is CG5 with the axial location at 27.1% C_a, which is between the two peaks of SMI but ineffective in SMI. The other groove is CG7 locating at 42.7% C_a. CG7 is selected for two reasons: 1) it locates near the second SMI peak, which is higher than the first peak near the leading edge; 2) it is also not far from CG5 which can be deemed as a comparison with CG5. As the two grooves show quite different effects on stall margin, they will be tested together with the smooth casing (SC, without treatment) in this paper in order to compare the impacts of the two grooves on stall inception.

In the experiments the steady measurements for the calculation of characteristic curve are considered first. The characteristic curve is expressed with the flow coefficient φ and pressure rise coefficient ψ, which are defined by Equations (1) and (2):

$$\varphi = \frac{V_1}{U} \tag{1}$$

$$\psi = \frac{P_{2,s} - P_{1,t}}{\frac{1}{2}\rho U^2} \tag{2}$$