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Flow measurements near the open surfaces of single circumferential grooves in a low-speed axial compressor

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A B S T R A C T

Circumferential grooves (CG) is an effective method to enhance the compressor stall margin with minor efficiency disturbances. The interaction between the groove and the blade passage is found to be responsible for the stall margin improvement (SMI) by many studies. The momentum transport across open surface of an individual groove could be an indicator to assess its effectiveness. These findings are all derived by numerical means. Two single grooves are chosen as the examples to demonstrate the needs of the experimental validation. In experiments, one groove, CG5 at 27% axial chord, produced less SMI than the other one, CG7 at 43% axial chord. Yet, many CFD simulations predicted just the opposite. In order to validate the numerical simulations, detailed flow structures are needed near the open surfaces of the casing grooves. However, such experimental results are still missing due to the difficulties of measurement, especially for the flow measurement inside the grooves. Aiming at providing reasonable experimental results for these casing grooves, a measuring technique is proposed in this paper. A special algorithm is utilized to obtain the time-averaged magnitudes of velocity components by using three hot-wire probes. The groove–passage interaction is recorded using the fluctuations of each velocity component and the frequency spectrum. Intensive interaction is detected for CG7. The experimental results demonstrate that the flow interaction between the groove and blade tip is crucial to the stability enhancement.

1. Introduction

Circumferential groove (CG) casing treatment is a method with less efficiency loss to improve the stall margin of axial compressor [1]. During the past decades, efforts have been dedicated to understand the mechanism by which the grooves improve the stall margin. In these studies, the removal of the passage blockage, the delay of the tip leakage vortex breakdown and the postponement of the tip leakage flow spillage are considered to be responsible for stall margin improvement.

It is recognized by many studies that the flow at the interfaces between the grooves and blade passages (the open surfaces of the grooves) plays an important role in improving the stall margin because the interaction between the flows in the blade passage and the grooves has to go through this open surface. Such interaction may be an essential parameter to indicate how every individual groove performs in a composed multiple groove configuration. A general picture by numerical simulations is that the grooves generate the “suction” flow from the blade passages into the grooves near the pressure side and shoot the flow back into the passages near the suction side. This “suction–injection” effect is correlated to many viewpoints that explain the stall margin improvement on a basis of numerical study. Muller et al. presented that the grooves are responsible for the repositioning of the trajectory of tip leakage flow (TLF) towards the trailing edge [2]. Shabbir and Adamczyk [3] quantitatively studied the flow interaction between the groove and the blade passage. By accounting the axial momentum distribution at the casing surface, the radial transport of the axial momentum through groove’s open surface is considered to be an indicator of the effectiveness for an individual groove. Legras et al. [4] extended this method into unsteady analysis, and they concluded that the radial velocity component across the opening surface is crucial for assessing the transport. The flow features at the groove–passage interface are also investigated in many studies, such as Chen et al. [5] and Nolan et al. [6]. Nan et al. [7] calculated the axial momentum balance for the tip gap. They reported that compared to the axial momentum transport in the blade passage, the axial momentum transport across the opening surface is quite small, which means although it is crucial, the axial momentum transport due to grooves is small compared with other directions. These findings are all based on numerical simulation.

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Nomenclature

C	chord length
V	flow velocity
U	tangential speed of the blade at mid-span
P	pressure
E	output voltage of hot-wire probe
Q	effective velocity for hot-wire probe
φ	flow coefficient
ψ	pressure rise coefficient
ρ	ambient density
h	normal sensitivity coefficient of single-wire probe
k	tangential sensitivity coefficient of single-wire probe
α	mounting angle of the single-wire probe
c_0 to c_4	coefficients for calculating the effective cooling velocity of hot-wire probe
m, K and H	intermediate variables in the solution of flow velocity

Subscripts

1	rotor inlet
2	rotor outlet
a	axial direction
r	radial direction
t	tangential direction
s	static parameter
tot	total parameter
stall	parameter corresponding to the point of stall inception
x, y, z	corresponding directions in the coordinate system of the single-wire probe

On the other hand, it is regarded that to accurately pursue the stalling process by simulation is a big challenge [8]. It can be evidenced from that one can hardly find a perfect match in SMI between the calculation and experiment [9–11]. The investigation of single-groove casing treatment is an example to show the inconsistent results reported from the experiments and numerical simulations. Houghton and Day [12] examined the SMI variation along the chord direction by shifting the single groove from leading edge to trailing edge. It is found that two peaks of SMI generated at 8% chord and 50% chord. Moreover, the most effective axial position is in the middle and rear part of the chord. However, CFD shows an exactly opposite trend, suggesting that the grooves locate at front part of the chord are more effective than those at rear part. Similar results are also found in authors previous study [13].

Henceforward, it is a necessary requirement to look deep into this interface and the inner groove, to gain an experimental data of this transportation, which is believed by the authors to be essential and irreplaceable before examining the flow details and exploring the flow mechanisms by CFD means. However, the highly three-dimensional, unsteady flow with quite complicated structure exist at the groove–passage interface which highly requires the spatial and temporal resolution of the measurements. The grooves are usually in millimeter order, which considerably restrains the measurement space and technique. In addition, the tip clearance is also very small, which is less than 1 mm for most of compressors, increasing the difficulties on mounting transducers or probes with traditional method and also challenges the spatial resolution. Henceforward, the traditional measuring methods are probably not the rational solution and experimental studies with this respect are seldom reported in public literatures according to the authors' knowledge.

To this end, the research goal of this paper is to propose a flow measurement technique at the groove–passage interface and provide the corresponding experimental data. Similar work can be found in the literature about slot-type treatment by Takata and Tsukuda [14], in which the hot-wire probes and total pressure probe were utilized to measure the flow pattern in the treated slots. Besides, some experimental studies about the measurements of the blade tip-region flow with high spatial and temporal resolution can also be taken as references, such as the work by Inoue and Kuroumaru [15] and by Weichert and Day [16]. In both of these studies, hot-wire probes were mounted in the tip gap and rotated to different orientations for the measurements. The data acquired by these probes and the unsteady pressure transducers mounted on casing were utilized to characterize the flow field by the specialized post-processing algorithm. In order to obtain the enough data about the flow field, the rotation of probes is necessary in these studies, which makes the measuring and data-reduction process quite complicated. However, for the circumferential groove case, the feasibility of the use of rotating probes is significantly suppressed due to the small dimension of groove width. Based on which, a special measuring and data processing method by hot-wire probes is designed and applied for the measurements at the groove–passage interface in this paper. Three hot wire probes are mounted at the open surface with different orientations, coupled with special data post processing method, the virtual "rotating" can be achieved. This process can be deemed as a simplified probe-rotating and data-reduction method which is similar to literatures [14] to [16], while it is easily to be performed in the narrow space of the groove. The overall-averaged velocity components are discussed first, and the groove–passage interaction is further studied by the periodic fluctuations of velocity components as well as the frequency domain analyses.

Two single-groove configurations with different axial locations are selected for these measurements, not only because one of which is effective in SMI and the other is ineffective, but also because the available numerical simulations predicted exactly otherwise [13]. The flows near the groove–passage interface are measured and compared between the two single grooves. Results of data processing with the passage phase-locking method are also given, which imply the different flow features exist for the ineffective groove. Due to the spatial revolution limit of the hot-wire probes and the measuring error of this method, the detailed local flow structure at the groove–passage interface corresponding to each passage could not be obtained by experimental means alone. However, the basic flow features relating with the groove–passage interaction are revealed experimentally. Based on these results, a possible flow structure at the groove–passage interface is proposed for the ineffective groove as the discussion in the last section. The experimental study described in this paper can hopefully initiate an idea on casing treatment inner flow field measurement and invite further investigations on truly understanding the flow mechanisms of stall margin improvement.

2. Experimental test-rig

The tested compressor

An in-house axial low-speed compressor with the single rotor structure is utilized for the experimental work about CG treatment in this paper. The structure of the test-rig is shown in Fig. 1 and the detailed parameters are listed in Table 1. In the previous studies [17], the SMI trend and stall inception type have been already studied in this test-rig. In this paper, the characteristic curves are measured in the same way with these previous studies.