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The impact of casing groove location on the flow instability in a counter-rotating axial flow compressor

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ABSTRACT

To make up the lack of the experimental and numerical investigations about the grooved casing treatment (CT) applied in counter-rotating axial flow compressors (CRAC), the effects of circumferential single grooved CT on the stability enhancement were investigated in the rear rotor of a low-speed CRAC with numerical simulations. The main purpose was to gain a better understanding of the application principle of casing groove and the associated control mechanisms in the CRAC. Parametric studies show that the optimal position of the groove should be located near the blade leading edge in terms of stall margin improvement (SMI) and efficiency enhancement at the near stall condition. Due to the impact of casing groove on tip leakage flow (TLF), the blade tip unloading effect, redirection effect and the compound effect of suction–injection are all beneficial to the SMI. Detailed observation of flow structures illustrates that it is more effective to improve flow stability by controlling the critical TLF released from about mid-chord and the stall inception process may be probably changed due to the direct effect of groove on the main TLF released near the blade leading edge. Additionally, the effects that the groove has on rotor outflow blockage, backward axial momentum flux and TLF momentum perpendicular to the blade tip camber inside the tip gap are also studied in the paper.

1. Introduction

Aerodynamic instabilities in the form of rotating stall and surge are major limiting factors for the stable operating range of compressor [1–4]. Generally, there are two types of stall inception phenomena during rotating stall process. One is the modal stall inception, which is initiated by long length-scale disturbances measured in terms of circumferential length. Another is spike-type stall inception which is initiated by short length-scale disturbances measured by blade pitches [5]. As one of passive flow control techniques, casing treatment (CT) is an effective approach to improve compressor flow stability. Hathaway reviewed a range of different CTs that have been reported in public literatures, including honeycombs, slots, self-recirculating treatment, and circumferential grooves [6]. Among the kinds of CTs, slot-based and groove-based CTs are most commonly investigated because of their processing simplicity and strong potential in terms of extending operating range. Generally, compared with slot-based CTs, the circumferential grooves can achieve moderate stall margin improvement (SMI) with limited efficiency loss. Therefore, circumferential grooves seem to have an advantage in practical use when considering both the stabilizing effect and efficiency drop [7].

Several studies have been conducted to determine the effectiveness of grooves at different locations to improve compressor stability and to provide guidance during the design process of grooved CTs. In 1972, Bailey experimentally studied the effect of groove location on the stall margin (SM) in a single stage axial flow compressor. It was found the greatest SMI is obtained when the grooves are located near the mid-chord [8]. Houghton and Day [9,10] conducted experimental investigations on low-speed axial compressors to study the effectiveness and mechanisms of casing grooves. The results showed that there were two locations on the casing where a single circumferential groove will generate a maximum SMI and one location where the casing groove produced the minimum SMI. The two effective locations were at about 8% and 50% axial chord of blade tip (Ca) respectively and the position corresponding to the minimum SMI was located near 20% Ca. Additionally, they also found that casing grooves give the greatest SMI when used in a compressor that exhibits spike-type stall inception, while modal activity before stall can dramatically reduce the effectiveness of the grooves. Sakuma et al. [11] have presented a detailed observation numerically on the effect of varying the axial location of single circumferential casing groove for a

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Nomenclature

Ca	Axial chord of blade tip
Cp	Static pressure coefficient $Cp = \frac{p}{P_1^*}$
d	Groove depth
m	Mass flow rate
p	Local static pressure
P_1^*	Inlet total pressure
U	Rotor tip speed
$u_\perp$	Velocity component perpendicular to blade tip camber
V	Velocity
w	Groove width
$y+$	Nondimensional wall distance
ρ	Density
η	Adiabatic efficiency
π	Total pressure ratio
ΔSM	Change of SM
$\Delta\eta$	Change of efficiency
ψ	Nondimensional mass flow rate
ϕ_x	Nondimensional local axial momentum flux intensity

Abbreviations

3D	Three dimensional
AM	Axial momentum
AR	Aspect ratio
CRAC	Counter-rotating axial flow compressor
CT	Casing treatment
IGV	Inlet guide vane
LE	Leading edge
NSP1	Near stall point1
NSP2	Near stall point2
OGV	Outlet guide vane
PS	Pressure surface
R1	Clockwise rotating rotor
R2	Anti-clockwise rotating rotor
SM	Stall margin
SMI	Stall margin improvement
SS	Suction surface
SW	Smooth wall
TE	Trailing edge
TLF	Tip leakage flow
TLV	Tip leakage vortex

transonic compressor. The results indicated that the maximum SMI was observed in the case where the groove was located about 20% *Ca* downstream of the blade leading edge (LE) and the stability enhancement effect was able to be improved even more by deepening the groove. Du et al. [12] investigated the impact of casing groove location on SM and tip leakage flow (TLF) in a low-speed axial compressor numerically and experimentally. The results indicated that the optimal groove location in terms of SMI was at about 57% *Ca* and that the location with the minimum SMI was at about 20% *Ca*. In addition, the movement of the interface between the TLF and incoming main flow throughout the stable throttling process for the worst groove casing is considerably different from that of the optimal groove casing.

Endeavors to gain better insight into the control mechanisms of grooved CTs have also been another hot topic with the development of numerical and experimental technologies [13–18]. However, there still exist disagreements in published literatures about how the casing grooves work effectively because the corresponding interaction of the grooves with the flow field in the tip region and the stall inception processes are not fully understood. Therefore, more work are still needed to be carried out to uncover the mechanisms of the grooves to enhance flow stability in the future.

In recent years, the counter-rotating axial flow compressor/fan stage (CRAC) arouse a greater interest due to the reason that counter-rotation enables to reduce the weight of a machine by eliminating of the stator blade row between the adjacent rotors [19,20]. To gain a deeper insight into the flow physics in CRAC, a large amount of work has been carried out on some major factors, including unsteady effects, inlet distortion, tip clearance effect, speed ratio of the two rotors and axial spacing between two rotors, etc. [21–30]. Results indicated that there exist many fresh characteristics and unique flow phenomena in CRAC compared with conventional compressor stages. However, up to now, there is limited information in the open literatures on the detailed investigation of CTs in CRAC except the work conducted by Pundhir et al. [31] experimentally. Three types of CTs, namely axial slots, axial skewed slots and circumferential grooves, had been examined in the paper. The results showed that the circumferential grooves type CT was the most suitable and the compressor stage efficiency had been found to be improved over a wide operating range including the off-design operation when a grooved CT was used. However, there was no further analysis about the detailed flow field in the paper and it is also uncertain whether the conclusions would apply to the present case as well. Therefore, it seems worthwhile to make a further study on the effectiveness and corresponding flow mechanisms of grooved CTs in the CRAC.

In order to make up the lack of the experimental and numerical investigations about grooved CTs used in CRAC, the focus of analysis in this paper will be mainly on (1) parametric studies are performed with respect to the axial location and groove depth of single casing groove; (2) the tip flow field in the CRAC is analyzed to gain understanding of the flow changes and explain the parametric study results. This paper is organized as follows. After the introduction of the investigated CRAC and the design of circumferential grooved CTs in Section 2, the numerical method and its validation are shown in Section 3 then. The parametric study results and the corresponding analysis of flow field are presented in Section 4. Finally, a list of conclusions is shown in Section 5.

2. Investigated rig and circumferential grooved CTs

2.1. Description of the investigated compressor rig

A low-speed two stage counter-rotating axial flow compressor was used for the numerical investigation in the current paper. The pictures and a cross-sectional diagram of the CRAC are shown in Fig. 1. The compressor contains four blade rows, i.e. inlet guide vane (IGV) with 22 blades, a clockwise rotating rotor (R1), an anti-clockwise rotating rotor (R2), and an outlet guide vane (OGV) with 32 blades. The total pressure ratio and mass flow of the CRAC at design condition is about 1.22 and 6.4 kg/s respectively. Table 1 lists the other main design parameters of the CRAC. Two AC motors are used to drive the two rotors respectively.

2.2. Design of circumferential grooved CTs

Previous studies have shown that the tip flow field in R2 is responsible for the spike-type flow instability of the CRAC [26,28,29]. Therefore, a total of ten circumferential single grooves over