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Research Paper

Numerical analysis of the circumferential grooves casing treatment in a counter-rotating axial flow compressor

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HIGHLIGHTS

- The stall margin and compressor performance at near stall point are both enhanced.
- Several contribution factors for the stall margin improvement are illustrated.
- The oscillations' change is found closely related to the stall margin improvement.
- The fluctuations with lower frequency are suppressed by the casing grooves.
- Flow stability is dominated by the tip leakage flow released from near mid-chord.

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ABSTRACT

The impact of the circumferential grooves casing treatment over the rear rotor (R2) in a counter-rotating axial flow compressor has been investigated based on numerical simulations. The main purpose is to understand the effects of grooved casing treatment on the unsteady flow behaviors and the corresponding mechanisms of the stability enhancement in the compressor. The results show that the interface between incoming main flow and tip leakage flow in R2 is pushed downstream obviously and the flow stability is enhanced with grooved casing treatment. The compressor performance at near stall condition is also improved remarkably. The blade loading below the grooves, the incidence angle near the blade tip and the backward axial momentum flux injected into main flow passage through the tip gap are all reduced, which is beneficial to the stall margin improvement. Frequency analysis near the blade tip of R2 indicates that the oscillations with lower frequency are suppressed by the casing grooves and the fluctuating intensity decreases, which also contributes for the enhancement of flow stability. Detailed observation of tip leakage flow structures illustrates that it is more effective to improve the flow stability by controlling the tip leakage flow released from near mid-chord.

1. Introduction

Aerodynamic instabilities in the form of rotating stall and surge are major limiting factors for the operating envelope of compressors, which has been studied almost continuously since the early development of the gas turbine engine [1–5]. To ensure the safety of the compression system in aircraft engine even at off-design condition, flow control techniques must be employed when the safe operating range is not satisfied by the aerodynamic design of the compressors. As one of the passive flow control methods, casing treatment has been widely investigated because of its effectiveness to improve the flow stabilities in compressors. In addition, compared with the slot-based casing treatment, the grooved casing treatment can offer greater mechanical integrity and cause smaller efficiency losses of the compressor [6].

Several studies have been carried out to explore the impact of single circumferential groove at various axial locations in terms of the stall margin improvement. It was found that there exists disagreement in the literatures about where the single circumferential groove should be located [7–10]. To offer better guidance for the groove design, many investigations have been conducted to reveal the flow mechanisms of the stall margin improvement by the grooved casing treatment.

Numerical investigation for the single circumferential groove by Sakuma showed that the stall suppression was thought to be due to the reduction of leakage flow momentum and the displacement of blockage region [9]. Through both numerical and experimental methods, Rabe and Hah revealed that the grooves improved the flow stability by decreasing the incidence angle at the blade

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Nomenclature

Cp	static pressure coefficient $Cp = (P - P_1^*)/(0.5\rho U^2)$
m	mass flow rate
p	local static pressure
P_1^*	inlet total pressure
T	numerical period
U	rotor tip speed
V	velocity
ρ	density
σ	standard deviation of static pressure
η	adiabatic efficiency
π	total pressure ratio
SMI	stall margin improvement
ψ	non-dimensional mass flow rate
ϕ_x	non-dimensional local axial momentum flux intensity

Abbreviations

AM	axial momentum
AR	aspect ratio
BPF	blade passing frequency
CT	casing treatment
FFT	fast Fourier transformation
LE	leading edge
NPE	near peak efficiency
NSP	near stall point
PS	pressure surface
R1	clockwise rotating rotor
R2	anti-clockwise rotating rotor
SS	suction surface
STD	standard deviation
SW	smooth wall
TE	trailing edge

leading edge [11]. Through numerical studies, Wilke and Kau found that the circumferential grooves improved the stall margin by suppressing the breakdown of tip leakage vortex [12]. By proposing a control volume method, Shabbir and Adamczyk indicated that the stall margin improvement was due to the radial transport of axial momentum across the interface between the groove and main flow [13]. Lu et al. also found that grooves near the blade leading edge deflected the tip leakage vortex most and these grooves stabilized the compressor most effectively by preventing the forward spillage phenomenon [14]. The study on the groove effects by Muller et al. showed that the reduction of the blade loading and the downward deflection of tip leakage vortex were responsible for the stall margin improvement [15]. Huang et al. [16] investigated the mechanisms of grooved casing treatment in a transonic compressor. The results illustrated that the significant stall margin improvement resulted from the reason that grooves near blade leading edge exerted positive influence on the leading edge spillage phenomenon and the breakdown of tip leakage vortex. Chen et al. conducted numerical simulations to study the impact of circumferential grooves casing treatment. It was found that the casing grooves obviously reduced the backward axial momentum flux through the tip gap [17]. An unsteady numerical investigation on the grooved casing treatment of stepped tip gap type by Reza and Sarallah showed that the casing treatment could retard the movement of the interface between the incoming main flow and tip leakage flow towards the rotor blade leading edge plane and suppress the reversed flow around the blade trailing edge [18]. From all the above investigations, one can see that there are still contradictions about how the casing grooves work effectively due to the complexity of the stall phenomenon and more work still needed to be conducted to reveal the mechanisms of the stall margin improvement by the grooved casing treatment.

Recently the counter-rotating axial flow compressor/fan stage arouse a great interest due to the reason that counter-rotation enables to reduce the weight of a turbomachine by removing of the stator between the two adjacent rotors [19]. In order to study the flow behaviors in counter-rotating axial flow compressor, many studies have been conducted and the results showed that there are many unique characteristics in counter-rotating axial flow compressor [20–29]. However, up to now, there is only one published paper conducted by Pundhir et al. [30] to investigate the effectiveness of casing treatment in counter-rotating axial flow compressor. The experimental results indicated that the grooved casing treatment was the most suitable for the counter-rotating axial flow compressor and the efficiency was enhanced over a wide operating range including the off-design operation when a grooved type of casing treatment was adopted. Therefore, it seems worthwhile to make more investigations for the effectiveness of grooved casing treatment and the corresponding control mechanisms in counter-rotating axial flow compressor. Additionally, there also still lacks a full understanding of the grooved casing treatment effect on the unsteady flow field in counter-rotating axial flow compressor.

To enrich the studies about circumferential grooves casing treatment in counter-rotating axial flow compressor, the focus of current paper will be mainly on the effect of grooved casing treatment on the unsteady flow behaviors inside and the corresponding control mechanisms of the stall margin improvement. The organization of this paper is shown as follows. After an introduction of the investigated counter-rotating axial flow compressor and the design of grooved casing treatment in Section 2, the numerical approach and its validation are given in Section 3 then. The numerical results and corresponding detailed analysis are presented in Section 4. Finally, a list of conclusions is shown in the last section.

2. Investigated compressor rig and the design of grooved casing treatment

2.1. Low-speed counter-rotating axial flow compressor test rig

The research object of present paper is a subsonic counter-rotating axial flow compressor at the National Defense Aerodynamics Laboratory of Airfoil and Cascade in Northwestern Polytechnical University (NWPU) in Xi'an. Two pictures and a cross-sectional diagram of the counter-rotating axial flow compressor are shown in Fig. 1. The compressor includes four blade rows, i.e. inlet guide vane with 22 blades, a clockwise rotating front rotor (R1) with 19 blades, an anti-clockwise rotating rear rotor (R2) with 20 blades, and an outlet guide vane with 32 blades. The compressor produces a total pressure ratio of about 1.22 at a mass flow rate of 6.4 kg/s at the near design point. Two motors are applied to drive the two rotors respectively through a gearbox, which allows for driving both rotors at different speed ratios. Some other main design parameters of the counter-rotating axial flow compressor are presented in Table 1.