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Numerical investigation into the effects of casing aspiration on the overall performance and flow unsteadiness in a counter-rotating axial flow compressor

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ABSTRACT

The impacts of casing aspiration with circumferential slot over the rear rotor on the overall performance and unsteady flow behaviors have been studied with numerical simulations in a counter-rotating axial flow compressor. The results indicate that casing aspiration is an effective active flow control method to expand the safe operating range of the compressor. The peak efficiency is always decreased to a different extent in the aspiration schemes and the best aspiration scheme is located at near 10% tip axial chord without significant peak efficiency loss. After the casing aspiration, both the relative inlet flow angle and the leading edge blockage are reduced obviously in the tip region. The angle between the exit direction of tip leakage flow (TLF) and axial direction is also reduced over the whole blade chord range, especially below the aspiration slots due to the local blade unloading effect. Additionally, the interface between the TLF and incoming main flow is pushed more downstream in the aspiration schemes and it is more effective to improve the flow stability by controlling the TLF released around mid-chord through casing aspiration. The intensity of both TLF and double leakage flow is attenuated and the overall oscillations inside are alleviated to a different extent in the aspiration schemes. Frequency analysis shows that the fluctuation of TLF with lower frequency component is suppressed by casing aspiration which is thought to be beneficial for the enhancement of stall margin.

1. Introduction

Compressor performance measured in terms of efficiency, pressure ratio, and stability is limited by the flow separation behaviors within compressors. As one of the effective active flow control methods to alleviate the flow separation, aspiration is a very promising technique to meet the requirement of the advanced compressors in the future and it provokes a great interest with an increasing number of researchers. Currently, the investigations about aspiration are mainly concentrated on the control of the boundary layer separation on blade suction surface (SS) or the three-dimensional (3D) hub corner separation in the compressor cascades or stages. It has been found that the flow control method of aspiration is practical with proper design of the aspiration slots/holes and the performance of compressor cascades or stages can be improved significantly [1–9].

The air bleeding system is essential to ensure safe operation of aircraft engines. Generally, the bleed air is needed for a variety of requirements including supplying the high temperature components with cooling air, engine inlet anti-ice and improving the stage matching of the compressor during operation at off-design points [10,11]. A large amount of studies have been conducted to explore the effects of air bleeding through the casing/hub endwall on the compressor performance [12–17]. Actually, the air bleeding can remove the low energy fluid from critical regions and mitigate the local flow blockage in compressors. Therefore, the design of air bleeding system can be combined with the active flow control method of aspiration and the compressor performance can be improved if the bleeding air is used to control the detrimental flow behaviors. For this reason, a lot of research have been performed systematically by Massachusetts Institute of Technology in cooperation with NASA Glenn Research Center and an aspirated compressor design system was set up finally [18–22].

It has long been known that the tip leakage flow (TLF) in the rotor tip region of an axial compressor has a critical influence on the overall performance and stability. Additionally, with modern compressor designs trending toward higher aerodynamic loadings and fewer stages, the effects of TLF will become more strong due to the increased relative tip clearance size, especially in the later stages [23–25]. Therefore, there is strong motivation to seek proper means to minimize the influence of TLF on the compressor perfor-

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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
$\overline{P}$	Time-average static pressure
U	Rotor tip speed
x	Radial direction
y	Tangential direction
z	Axial direction
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

Abbreviations

3D	Three-dimensional
BPF	Blade passing frequency
CRAC	Counter-rotating axial flow compressor
DLF	Double leakage flow
FFT	Fast Fourier transformation
IGV	Inlet guide vane
LE	Leading edge
OGV	Outlet guide vane
PS	Pressure surface
R1	Clockwise rotating rotor
R2	Anti-clockwise rotating rotor
SS	Suction surface
STD	Standard deviation
SW	Smooth wall
TE	Trailing edge
TLF	Tip leakage flow

mance through both active and passive flow control approaches [26–30]. However, at present there are only several studies of applying casing aspiration on the control of TLF to improve the compressor performance and stability [31–34]. Additionally, very little study has been carried out on the effectiveness of different aspiration locations on the casing and the corresponding control mechanisms. There has also been limited information so far in the open literatures about the effects of casing aspiration on the unsteady flow behaviors inside and the flow structures in the tip region.

In recent years, the counter-rotating axial flow compressor (CRAC) has been considered as a promising technology due to the reason that counter-rotation enables to lighten the engine weight by removing the stator blade row between the adjacent two rotors [35]. To study the flow physics in CRAC, many works have been conducted on the important factors, including axial spacing between two rotors, unsteady effects, and inlet distortion, etc. [36–42]. The results showed that there were many unique flow phenomena in CRAC compared to the conventional compressors. A counter-rotating stage might produce a stall-free characteristic for certain rotor under some conditions [43,44]. Shi et al. [45] conducted an experimental investigation of a counter-rotating compressor with aspiration both on the casing and blade suction surface of the outlet guide vanes at 70% design speed. They found that aspiration can improve the compressor characteristics and the best aspiration methodology varies along the operating line. At the near stall condition, aspiration from the tip region of the rear rotor can obviously increase the efficiency and the total pressure ratio. Pundhir et al. [46] investigated 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. However, there is still lack of sufficient investigations about the application of active flow control techniques in CRAC and it is worthwhile making detailed studies on the effectiveness of casing aspiration at different locations in CRAC.

Therefore, to better understand the effects of casing aspiration with circumferential slot on the performance and stability enhancement of CRAC and provide reference for the application of aspiration technique in the advanced aircraft engines, the focus of the analysis in current work will be on (1) where the circumferential aspiration slot should be located according to the change of stall margin and efficiency, (2) what is the corresponding control mechanisms of the aspiration schemes, and (3) how does the TLF structures and unsteady flow behaviors change after the application of casing aspiration. This paper is organized as follows. Firstly, the investigated compressor rig and the design of casing aspiration slot are introduced in Section 2. Secondly, the numerical method and its validation are shown in Section 3. Thirdly, the numerical results and the corresponding discussion are presented in Section 4. Finally, a list of conclusions is summarized in the last Section.

Table 1
The main design parameters of the two rotors.

Design parameter	R1	R2
Tip clearance (mm)	0.5	0.5
Blade number	19	20
Hub-tip ratio	0.485	0.641
Rotational speed (rpm)	8000	−8000
Tip blade chord (mm)	83.2	76.9
Tip speed (m/s)	167.6	167.6

2. Research compressor rig and the design of casing aspiration slot

2.1. Subsonic counter-rotating axial flow compressor test rig

The configuration studied in the present paper is a low-speed counter-rotating axial flow compressor at the National Defense Aerodynamics Laboratory of Airfoil and Cascade in Northwestern Polytechnical University (NWPU) in China. Two pictures and a cross-sectional diagram of the compressor are presented in Fig. 1. The CRAC includes four blade rows, i.e. inlet guide vane (IGV), a clockwise (seen from inlet) rotating front rotor (R1), an anti-clockwise rotating rear rotor (R2), and an outlet guide vane (OGV). Their blade counts are 22, 19, 20 and 32 respectively. The two rotors are driven by two AC electric motors with frequency controller through a gearbox, which allows the two rotors to run at any speed combination from 0 to 8000 RPM. The total pressure ratio and mass flow rate of the CRAC at near design condition are about 1.22 and 6.4 kg/s respectively. Some other main design parameters of the compressor are shown in Table 1.

2.2. Design of the circumferential aspiration slot on the casing

Past researches have indicated that the flow field in the tip region of R2 is responsible for the flow instability of the CRAC [38,