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Research Paper

# Investigation on axial effect of slot casing treatment in a transonic compressor

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## HIGHLIGHTS

- The relative importance of the mechanisms of slot casing treatment is obtained.
- The bleeding and injecting effect is the most important mechanism for the slots.
- Effective slots should cover the tip leakage vortex and boundary separation zone.

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## ABSTRACT

This paper reports the effect of the axial position of the slot casing treatment on the performance of transonic compressor NASA Rotor 67 by unsteady numerical simulation. The interaction of the recirculation in the slots and flow near the blade tip is analyzed to understand the flow mechanisms. The relative importance of the mechanisms of stall margin improvement due to the slot casing treatment is evaluated with the relative weight method. The results show that the bleeding and injecting effect caused by the recirculation is the most important factor that affects the blockage in the blade tip region, which determines the stall margin improvement. When the slots cover the initial position of the tip leakage vortex (TLV) and the boundary layer separation zone downstream the shock, the recirculation is stronger due to the larger pressure difference between the front and rear part of the slots. Consequently, the slot casing treatment can reduce the blockage near the casing more effectively, which results in a larger stall margin improvement. Shifting the slots upstream or downstream will reduce the driving force for the recirculation and the effect extent on the low energy fluid of the slots, which decreases the stall margin improvement.

## 1. Introduction

The aero engines develop towards the direction of high thrust-weight ratio, low fuel consumption and wide stable operating range. This requires the compressor to have high stage loading, high efficiency and high stall margin. For highly loaded transonic compressors, the complex flow structures near the blade tip including the tip leakage flow, shock and boundary layer separation can induce flow losses and instability [1–3], which have significant effect on the performance of compressors. It has been indicated that the leakage vortex is a key factor for the flow instability if the blade loading does not exceed the stability limit near stall. The interaction between the tip leakage vortex and the shock can generate a low momentum region downstream the shock. The tip leakage vortex breakdown can occur if the intensity of the interaction exceeds the vortex breakdown limit [4–6]. As the mass flow rate decreases, the tip leakage vortex moves upstream and causes large blockage region near the blade tip, which leads to the stall of the compressor [7]. If the blade loading exceeds the stability limit near stall, boundary layer separation occurs at the suction side. Then the boundary layer separation causes blockage in the blade passage and contributes to the stall of the compressor [8].

In order to extend the stable operating range of compressors, the researchers have proposed a variety of casing treatments [9–11]. One of the various casing treatments is the configuration which consists of a discrete number of slots. The slot casing treatment is capable to improve the stall margin of compressors of significantly [12,13]. Many investigations have been conducted to reveal the effect mechanisms of slot casing treatments on the compressor performance and achieve proper slot geometries.

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**Nomenclature**

| | |
|---|---|
| $A$ | area (m$^2$) |
| $B$ | blockage for outer 80% span |
| CT | casing treatment |
| $D$ | position of the shock |
| $L$ | normalized circumferential length |
| $L_u$ | difference between the inlet and outlet tangential component of relative velocity |
| M | meridional direction |
| $M_r$ | normalized recirculating mass flow of the slots |
| $\dot{m}_c$ | mass flow of the compressor (kg/s) |
| $\dot{m}_r$ | recirculating mass flow of the slots |
| $\dot{m}_s$ | bleeding or injecting mass flow of the slot |
| NS | near stall |
| $P$ | averaged pressure difference at 98% span (Pa) |
| PR | total pressure ratio |
| PS | pressure surface |
| R | radial direction |
| SC | smooth casing |
| $SM$ | stall margin |
| SS | suction surface |
| T | tangential direction |
| TLV | tip leakage vortex |
| V | absolute velocity |
| $W$ | relative velocity |
| $W_m$ | meridional component of relative velocity |
| $W_u$ | tangential component of relative velocity |
| $W_z$ | axial velocity |
| X | vertical radial direction |
| Y | horizontal radial direction |
| Z | axial direction |
| $\alpha$ | angle between the tip leakage vortex trajectory and the axial direction (°) |
| $\beta$ | relative flow angle (°) |
| $\varepsilon_i$ | relative weight |
| $\zeta_n$ | absolute vorticity coefficient |
| $\rho$ | density |
| $\omega$ | rotor angular velocity |

Wilke et al. [14] numerically investigated the impact of the slot casing treatments on the performance of a transonic compressor. The vortex flow in the slots bled fluid out of the blade passage and injected it back into the main flow upstream. This effect could suppress the tip leakage vortex and was responsible for the stall margin improvement. Two configurations with different axial positions were studied. Configuration 1 is positioned from 7.5% to 92.5% chord. Configuration 2 is shifted upstream and covered only the upstream 25% chord. The two configurations improved the stall margin identically. Whereas, configuration 2 had less effect on the flow field and shock than configuration 1, so configuration 2 obtained higher efficiency than configuration 1. Another investigation [15] also indicated that the effectiveness and efficiency of the slot casing treatments relied much on the position of the slots. The downstream positioned slots obtained larger stall margin improvement but induced higher efficiency penalty than the downstream positioned slots. Lu et al. [16] numerically investigated the slot casing treatments with two different axial positions on a transonic compressor stage. It indicated that the proper position for stall margin improvement should have its forward end cover the tip leakage vortex initial position and its aft end cover the high pressure and stagnation region downstream of the passage shock. Because the high energy flow after the shock can be used to re-energize the tip leakage vortex. Zhu et al. [17] and Lu et al. [18] investigated the effect of slot casing treatments with several different axial positions on the performance of axial compressors. The main mechanism for delaying stall was attribute to the tip leakage vortex towards the trailing edge. The best configuration in terms of stall margin improvement and efficiency was obtained. But the coupled flow features through the blade passage and the different slot casing treatments were not compared. Brignole et al. [19] and Hembera et al. [20] conducted parametric investigations on the slot casing treatments for transonic compressors. Some parameters such as entering mass flow coefficient, geometrical efficiency and rothalpy rise coefficient were proposed to evaluate the slot casing treatments. These parameters helped to quantitatively compare the flow in the slots and the blade tip flow for different casing treatment configurations. Streit et al. [21,22] and Brandstetter et al. [23] investigated the effect of an axial-slot casing treatment in the rotor's leading edge region. Both numerical simulation and experiment showed that the slots could remove the blockage region caused by the interaction of the shock and tip leakage vortex, resulting in the downstream repositioning of the shock, which improve the stability. Ma et al. [24] studied the effect of axial-slot casing treatment on the peak efficiency of the compressors numerically. The slots covered the whole tip chord. An equation derived from the Denton's leakage mixing model is used to evaluate the tip leakage loss. Based on this analysis, the slot casing treatments that can improve the peak efficiency of the compressors were designed.

In general, the blade tip flow structures change significantly along the blade passage downstream in transonic compressors. The axial position of the slots has great effect on the interaction between the slots flow and the near casing flow. But the guidelines that help to design the axial position of slot casing treatments for stall margin or efficiency are still not clear. The optimum relative position between the slots and the blade tip flow structures including the shock, tip leakage vortex and boundary layer separation remains to be explored. And further investigation on the variation of the coupling flow through the blade passage and slots with different axial positions is necessary.

For these reasons, a study on the effect of the axial skewed slot casing treatments with four typical axial positions on the performance of a transonic compressor NASA Rotor 67 is performed in this paper. The investigation is implemented with unsteady numerical simulations.

## 2. Investigated compressor and numerical method

### 2.1. Investigated compressor

The transonic axial compressor NASA Rotor 67 was adopted in this investigation. The detail geometry and performance parameters of NASA Rotor 67 can be found in Ref. [25]. Some main design parameters are listed in Table 1. The rotating stall of NASA Rotor 67 occurs in the blade tip region, which is related to the tip leakage vortex. Thus the rotor is suitable for the investigation of casing treatment.

### 2.2. Numerical method

The commercial CFD solver NUMECA/EURANUS was used for the numerical simulation. The simulation was based on the turbulent Favre Reynolds averaged Navier-Stokes equations in the rotat-