MECHANISM ON THE INTERACTIONS OF ROTOR TIP FLOW WITH SLOT-TYPE CASING TREATMENT IN A TRANSONIC COMPRESSOR STAGE

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ABSTRACT

Aiming to reveal the influence mechanism of casing treatment on rotor tip flow structure, unsteady numerical method was used to study the effects of slot-type casing treatment (SCT) in a transonic compressor. The results showed that the tip flow field appeared obvious periodic flow characteristics with SCT at smooth casing near stall condition. When the rear edge of slot passed through the rotor pressure surface, the tip leakage flow kinked and was sucked into slots, yet significantly weakened when the rear edge of slot passed through the rotor suction surface. Meanwhile, the flow patterns in the slots change periodically with the variation of the relative position of rotor and slots. Furthermore, with the compressor throttling, obvious vortex structure evolution appeared in rotor tip region. At larger mass flow rate, the tip leakage vortex and corner vortex induced by SCT evolved almost at the same time, resulting in a large range of flow field pulsation in the rotor tip region. However, the interaction between corner vortex and tip leakage vortex happens and dominates at lower mass flow rate. As a result, the SCT gradually loses the ability of stability extension.

INTRODUCTION

Casing treatment (CT) has been proved to be an effective passive control method for expanding compressor stability since its discovery (Koch, 1970). After years of development, various types of CT have come to the fore, such as groove-type, slot-type, tip injection and self-recirculation. Among the different approaches, slot-type CT (SCT) has been found to be the most effective (Hathaway, 2007).

According to the existing literature, research on SCT can be divided into two categories (Sun et al. 2019). One is the geometric parameterization design of SCT, and the current challenges is how to design and choose the geometric parameters of SCT to obtain maximum stability margin, while reducing efficiency penalty. In order to achieve this goal, lots of methods such as experimental tests (Fujita et al. 1984; Alone et al. 2016), design of experiments (Du et al. 2017) and optimized design (Goimis et al. 2013; Zhu et al. 2020) have been implemented, and many beneficial results have been obtained. The other is the stability extension mechanism with SCT. In general, the common understanding on the role of SCT is: the SCT can effectively alleviate the tip blockage with the help of pressure difference between pressure surface and suction surface, and the recirculation flow in slots is key factors. However, it is difficult to get unified explanation for the stability extension mechanism with the change of compressor models, different operating speeds even different throttling conditions. Even so, considerable effort has already been invested to understand the flow mechanism involved with SCT.

Numerical studies by Wilke et al. 2004, using a semi-circle slot-type CT, pointed out that the stabilizing effect of axial slots mainly results from their impact on the tip leakage flow and its resulting vortex. Lu et al. 2006 also found that the bend skewed slot casing treatment was able to extend the stall margin of a compressor by repositioning of the tip clearance vortex further towards the trailing edge of the blade passage, and delaying the forward movement of tip leakage vortex. Schnell et al. 2011 implemented detailed time-accurate simulations in a transonic compressor stage with slot-type CT. The results showed that breakdown of tip leakage flow is delayed under the influence of the casing treatment compared with
the smooth casing, attribute to the injection effect of CT in the low pressure region. Zhang et al. 2019a and Zhang et al. 2019b presented the adequate experimental and numerical results in a subsonic axial compressor subjected to various configurations of SCT. They deemed that SCT can change the radial distributions of the rotor inlet and outlet relative airflow angles, meanwhile the sucked flows formed inside the slots improve the rotor stability more easily than the injected flows. Recently, researches have a deeper acquaintance of the stability enhancement mechanism of slot-type CT, with rapid development of visualization measurement technology, such as hot wire sensor, endwall dynamic pressure measurements and particle image velocimetry (PIV) measurements. Alone et al. 2014 used the hot wire sensor to capture the oscillations in the inlet axial and tangential velocities, and emphasized that the reduction of oscillation extents is the key role of CT in stability extension. Particle Image Velocimetry (PIV) measurements taken by Brandstetter et al. 2015 showed the CT could affect the blockage zone, secondary flow and shock structures in the blade tip region. The flow field structures in tip region with SCT in a subsonic compressor was studied by Chen et al. 2017 in details. They concluded that SCT can reduce the blockage induced by tip leakage vortex and restrain the appearance of backflow vortex.

According to the above results, it can be concluded: (1) The majority of previous studies only focused on the stability enhancement mechanism of SCT from the view of steady or time-average effects, the research on the unsteady effects of SCT and the evolution of flow field was rare. (2) Although reviewers gradually recognized the importance of shock structures and tip leakage vortex, further studies were still needed to reveal the complex flow field structures with SCT, especially in rotor tip region. Motivated by these questions, the effects and associated change of flow field structures by slot-type CT on a transonic axial compressor were studied through time-accurate unsteady simulations. The organization of this paper is as follows: the configurations of compressor stage and SCT are described in Section 2, the numerical method and grid is introduced in Section 3. In Section 4, flow field structures and stability extension mechanism involved with SCT are presented and discussed. Finally, main conclusions are summarized in Section 5.

**COMPRESSOR AND CASING TREATMENT CONFIGURATIONS**

The NASA stage 35 is used throughout this paper, previous experiments and numerical results carried out indicated that the compressor is inclined to spike-type rotating stall. As stated by Greitzer et al. 1979, casing treatment is especially suitable and effective for tip-critical compressor. NASA stage 35 is very representative transonic compressor stage, which was designed by NASA Lewis research center in 1978 to verify the influence of aspect ratio and load on compressor performance. It consists of 36 rotors and 46 stators, the design rotational speed is 17188rpm, with the stage total pressure ratio 1.82 at design mass flow 20.18 kg/s. According to Reid et al. 1978 and Chima 2009, the rotor gap (0.4 mm) and stator gap (0.76 mm) was consistent with experimental value. For reducing computing time, the computational domain is reduced to 3:4 passages, as shown in Figure 1. The inlet is located 4.5 times rotor tip axial chord(C_a) upstream of rotor leading edge and the outlet is 2C_a downstream of stator trailing edge.

The configurations of SCT are illustrated in Figure 1(b). Refering to Wilke et al. 2004, the structure of SCT is designed to semi-circle, and 45 degrees at radial direction consistent with the rotation direction of rotor. Detailed parameter values of SCT are following: the slot axial length is 0.85C_a with a overlap 0.5C_a above the rotor, the slot depth is 12 mm, the slot width is about 5.5 mm, the slot number for whole annular is 144, so the open area ratio of SCT is 50%.

![Figure 1 Computational domain and SCT configuration for Stage 35. (a) Computational domain; (b) SCT configuration.](image-url)
NUMERICAL METHODOLOGY
The commercial CFD solver, NUMECA 2011 is used in current calculations. In the solver, a second-order cell-centered finite volume scheme is used for spatial discretization, and four-step Runge-Kutta scheme for time marching under the relative frame of reference. The two equation k-epsilon turbulence model is applied to capture turbulence closure. The computational grids of compressor stage and SCT are shown in Figure 2, which are generated by IGG/Autogrid5. For the rotor/stator passages, an O4H topology is adopted. The single passage mesh is generated firstly then duplicated to the whole computational domain. The tip gap is meshed with butterfly topology with 25 points in the radial direction. As a result, the mesh for single blade passage consisted of 1.2 million (rotor) and 0.7 million (stator) nodes, which meets the requirements of grid independence. For SCT, the butterfly-grid topology is used, and the grids in single slot are divided into 69×45×25 points in axial direction, span-wise direction and pitch-wise direction. As a whole the grid points in total domain up to 7 million, and the grid density was increased towards all solid boundaries to keep $y^+ < 2$. Besides, multi-grid, local time step and implicit residual smoothing are used to speed up convergence.

![Figure 2 Computational mesh. (a) 3D mesh; (b) B2B mesh; (c) SCT mesh.](image)

For unsteady simulations, the implicit dual time stepping method is used to solve the equations. To capture the unsteady flow phenomenon sufficiently, the physical time step is about $3.2 \times 10^{-6}$ s, which represents 30 physical time steps in one rotor blade pitch. In each physical time step, 20 virtual time steps are adopted for solving steady problem. Based on previous experience (Wu et al. 2019), the physical and pseudo time step are adequate for unsteady simulations. During the numerical simulation, the constant total pressure 101325 Pa, total temperature 288.15 K and axial flow condition are set at the inlet boundary, and static back pressure at the outlet boundary. In addition, adiabatic and no-slip boundary conditions are applied at all solid walls. To obtain accurate near stall mass flow, back pressure is increased gradually to get last convergent solution, with an increment of 100 Pa when approaching the stall limit.

![Figure 3 Experimental and Numerical performance maps for stage 35. (a) Total pressure ratio; (b) Adiabatic efficiency.](image)

In order to verify the accuracy of the numerical method, Figure 3 presents the comparison of stage performance at three rotational speeds (100%, 90% and 70% design speed), where Exp and Cal represent the experimental and calculation results, and discrete solid points (identified by Unsteady 100, Unsteady 90 etc.) are unsteady results. As can be seen, the
numerical simulation results are in good agreement with the experimental results, the flow range from the choked flow rate to near stall flow rate is calculated accurately at different rotational speeds. The total pressure ratio and adiabatic efficiency are both within the experimental error limits, especially for near stall points. Besides, it can be found that the unsteady results are closer to experimental results than steady results. As a result, the unsteady numerical method in this paper is adequate to be used to study the effects of SCT on compressor performance and reveal the mechanism on the evolution of tip flow structures.

RESULTS AND DISCUSSION

In the following paragraph, a detailed discussion about the effects of SCT on compressor performance and the interactions between the rotor tip region flow structure and SCT slots will be presented. We have studied the flow fields of compressor at all three rotational speeds, but only the flow fields at 90% design rotational speed are discussed limited to the length of the article.

**Compressor overall performance**

![Figure 4 Compressor performance maps with and without SCT.](image)

The compressor performance maps of total pressure ratio with and without SCT are shown in Figure 4, where the symbol $\pi^*$ represents the total pressure ratio, and the symbol $\phi$ represents mass flow, which is normalized by choked mass flow with smooth casing (SC). Arrows labeled with “SCNS” and “CTNS” represent the NS points with SC and CT respectively. With the effects of SCT, significant stability margin enhancement is obtained. Compared with SC, higher total pressure ratio and smaller mass flow rate are shown with SCT. Visualization flow fields analysis will be carried out below to figure out the stability enhancement mechanism involved, and the flow field structures with SCT will also be analysed in details. Note that, the mass flow condition for analysing is the same at SCNS.

**Frequency domain characteristics of tip flow fields**

Figure 5 shows the FFT results of sample points at different axial locations in reference frames at 98% blade span, the sample points are equidistant distribution from the leading edge (LE) to trailing edge (TE), which can be seen in Figure 1(a). By contrast, FFT results of two key sample points are also be shown in Figure 5(b), their axial locations corresponding to LE and 20%Cₘₐₓ. As can be seen, the difference is obvious with and without SCT. At smooth casing, the frequency domain in relative frame shows a predominance of BPF and its higher harmonics. However, under the effect of SCT, the frequency domain in relative frame shows a predominance of 4 BPF, and lower amplitude of static pressure is observed compared with SC. Besides, the maximum amplitude at LE with SC indicates that tip flow unsteadiness related to flow fields at LE dominates, and yet the maximum amplitude at 20%Cₘₐₓ with SCT demonstrates that the unsteadiness of flow fields at LE is weakened by SCT. So, the following discussion will focus on the change of flow field at LE with and without SCT, to establish a correlation with the frequency domain characteristics of tip flow fields.
Figure 5 FFT results of numerical sample datas. (a) All sample points; (b) Key sample points.

In order to observe the distributions of static pressure amplitude at rotor tip region, Figure 6 and Figure 7 illustrate the contours of root mean square (RMS) static pressure at 98% blade span, pressure surface (PS) and suction surface (SS) with and without SCT. The value of $P_{\text{rms}}$ can be derived from the following equation:

$$P_{\text{rms}} = \sqrt{\frac{1}{N} \sum_{i=0}^{N} (P(t) - \overline{P})^2 / (0.5 \rho \cdot U^2)}$$

Where, $P(t)$ and $\overline{P}$ represents the instantaneous static pressure and averaged static pressure, and $U_t$ represents the tip tangential velocity.

Figure 6 Contours of root mean square (RMS) pressure amplitude at 98% blade span with and without SCT. (a) SC; (b) CT.

Figure 7 Contours of root mean square (RMS) pressure amplitude at PS and SS with and without SCT. (a) SC; (b) CT.
As is evident, the distributions of static pressure amplitude emerge obvious difference with/without SCT. For SC, static pressure disturbance induced by the detached shock wave can be seen as a long and narrow contour, and the maximum pressure amplitude behind shock wave mainly concentrates in rotor LE (Figure 6(a)). The contours at PS and SS indicate that the pressure disturbance at PS contributes to the unsteadiness of tip flow fields. For SCT, however, two distinct zones are obviously related to the change of flow fields. The first zone is the location change of front shock, it can be seen that the shock wave and relevant pressure disturbance moves downstream under the effect of SCT. The second zone is the excitation zone, which communicates the flow of PS with that of SS. As a result, the tip leakage flow covered by SCT is strengthen and the maximum pressure amplitude locates 20%Cax, which is also can be found in the contours at PS and SS (Figure 7(b)).

Subsection summary: (1) The frequency domain characteristics of tip flow field shows obvious difference with/without SCT, a predominance of BPF and its higher harmonics appears at SC, yet a predominance of 4 BPF emerges under the effects of SCT. (2) Two distinct zones, front shock wave moving downstream and excitation zone by SCT, contributes to the change of frequency domain characteristics of tip flow field under the effects of SCT.

Transient flow characteristics of tip flow fields

In order to further reveal the evolution mechanism of tip flow fields with and without SCT, some transient flow field structures will be discussed in followings. The discussion starts with the tip leakage vortex (TLV) and passage blockage distributions. Figure 8 depicts transient isosurfaces of Q-criterion and 3D limiting streamline distributions of TLV, the reversed flow region (grey zones) at 98% blade span is used to be the indicator of passage blockage. The isosurface of TLV is rendered with helicity (Furukawa et al. 2000) and defined as follows:

\[ H_n = \frac{\mathbf{\zeta} \cdot \mathbf{\omega}}{\mathbf{\rho} \cdot \mathbf{v}} \]  

Where \( \mathbf{\zeta} \) and \( \mathbf{\omega} \) denote vectors of the absolute vorticity and the relative flow velocity, respectively.

Figure 8 Isosurfaces of Q-criterion (1e8 s\(^{-1}\)) rendered with helicity for TLV and distributions of 3D streamline of Wxyz. (a) SC; (b) CT.

For SC, the breakdown of TLV is the main flow characteristic of tip flow fields, accompanied by the twisted vortex structure and vortex shedding. As a result, the reversed flow zone caused by TLV breakdown results in the passage blockage at PS side of rotor LE. Under the effect of SCT, the breakdown of TLV is restrained, so the passage blockage has been greatly alleviated, which benefits from the suction effect and injection effect by SCT. As is evident, the blockage induced by TLV is draw off at the rear of slot, and the flow are injected into passage main flow at front edge of slots.

In order to establish the correlation between the change of tip flow structures and frequency domain characteristic, the instantaneous evolution of TLV structures in one rotor period with and without SCT are shown in Figure 9. As shown in Figure 5, a predominance of BPF and its higher harmonics appears at SC. Figure 9 reveals the change of TLV structure under this frequency. At 1/30T, the TLV breakdown happens. As the rotor continues to turn, the TLV structure becomes
twisted and towards rotor LE at PS of adjacent blade at 6/30T and 11/30T. As a result, vortex shedding appears and develops downstream at the rest moment of the rotor period. Under the effect of SCT, the phenomenon of TLV breakdown disappears and the vortex core of TLV is closer to SS. With the excitation of suction and injection effect of SCT, the vortex core fluctuates, but the effect of SCT submerges the disturbance frequency of TLV. As a result, a predominance of 4 BPF emerges under the effects of SCT.

Figure 9 Isosurfaces of Q-criterion (1e8 s^{-1}) rendered with helicity for TLV in one rotor period with/without SCT. (a) SC; (b) CT.

Interactions of tip flow fields and slots of SCT
The following discussions are focused on the interactions of tip flow fields and slots of SCT, so the transient flow field distributions at some meridional planes or side sections of slots are presented. First of all, the contours of absolute vorticity at meridional plane in one rotor period are described in Figure 10, the shadow area in the figure represents the expansion of TLV. The absolute vorticity is normalized as follows:

$$
\vec{\omega}_a = \frac{1}{2U_s}.
$$

(3)

As can be seen, the expansion of TLV resulted from TLV breakdown leads to dramatic passage blockage at smooth casing. It is the main reason for tip flow instability, and severe passage blockage presumably triggers compressor into rotating stall when the compressor is throttled to lower mass flow. With SCT, the TLV is well confined near blade SS, so the expansion of TLV is greatly reduced. The change of TLV attribute mainly to two reasons: one is that the accumulated low energy flow at rear of passage is removed under the suction effect of SCT, so the tip leakage flow is easy to flow downstream. The
other is that the recirculation formed in slots elevates the momentum of tip leakage flow, so the tip leakage vortex is more concentrated and less prone to break down.

Figure 10 Contours of absolute vorticity at meridional plane in one rotor period. (a) SC; (b) CT.

For deeply understanding the interaction mechanism of tip flow field and slots, the contours of static pressure at 98% blade span and flow patterns in slots in one rotor period are depicted in Figure 11. The static pressure is normalized by inlet total pressure, the absolute velocity vector superimposed on the normalized absolute vorticity is used to describe the flow patterns in slots.

Figure 11 Contours of static pressure at 98% blade span and flow patterns in slots in one rotor period at SCNS condition.

In one rotor period, the flow patterns in the slots change periodically with the variation of the relative position of rotor and slots. There are three main flow patterns, which are named as Pattern A, Pattern B and Pattern C. In general, the Pattern A is the most effective recirculation flow in slots, it appears when the rotor rotates across the slot. Driven by the pressure difference of PS and SS, the tip leakage flow is sucked into slot and a counter-clock recirculation flow is formed, which is
the most important reason for SCT enhancing compressor stall margin. As rotor rotates, the Pattern B appears when only the slot rear covers the rotor. In this condition, the driving force is insufficient to provide the recirculation flow in slots, so a corner vortex emerges in slots. When the rotor continues to rotate until the rotor is completely away from the bottom of the slot, the Pattern C appears as the indicator of invalid recirculation flow in slots, because of a pair of counter vortex emerges in slots. As a result, the flow patterns vary alternately in one rotor period. Owing to this, the TLV exists a slight disturbance as shown in Figure 9(b).

Furthermore, the contours of absolute vorticity at meridional plane at SCNS and CTNS conditions with SCT are shown in Figure 12 to study the interaction mechanism of tip flow fields and slots of SCT at different mass flow conditions. At SCNS condition, the corner vortex (CV) exists only in slots due to the effective control of TLV by SCT, by constrast the TLV is concentrated and higher-energy. As a result, the SCT brings about adequate stall margin enhancement. When the compressor is further throttled, the interaction between CV and TLV happens and dominates at CTNS condition. With the appearance of this phenomenon, the SCT gradually loses the ability of stability extension.

**CONCLUSIONS**

In this paper, unsteady numerical studies are carried out in a transonic with slot-type casing treatment to reveal the influence mechanism of casing treatment on rotor tip flow structures. The conclusions can be summarized as follows:

1. In investigated compressor, the frequency domain characteristics of tip flow field show obvious difference with/without SCT, a predominance of BPF and its higher harmonics appears at SC, yet a predominance of 4 BPF emerges under the effects of SCT.
2. At SC, the breakdown of TLV is the main flow characteristic of tip flow fields. TLV breakdown, twisted vortex structure and vortex shedding results in the unsteadiness of tip flow fields. Under the effects of SCT, two distinct zones, front shock wave moving downstream and excitation zone by SCT, contributes to the change of frequency domain characteristics of tip flow field. With the excitation of suction and injection effect of SCT, the vortex core fluctuates, but the effect of SCT submerges the disturbance frequency of TLV. As a result, a predominance of 4 BPF emerges under the effects of SCT.
3. The analysis on the interactions of tip flow fields and slots of SCT shows that the flow patterns in the slots change periodically with the variation of the relative position of rotor and slots. Driven by the pressure difference of PS and SS, the tip leakage flow is sucked into slot and a counter-clock recirculation flow is formed, which is the most important
reason for SCT enhancing compressor stall margin. Besides, the interactions between CV and TLV can be a indicator of invalid recirculation flow in slots.

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REFERENCES


