Effects of Sloped Trench Casing Treatment Combined with Air Injection on Aerodynamic Performance of a 1.5 Stage Axial Flow Compressor

Zou Kai-kai, Liu Yong-bao, Yu You-hong* and He Xing
School of Power Engineering, Naval University of Engineering

yyh_work@aliyun.com

Abstract. A new mode, sloped trench casing treatment combined with air injection, was designed and introduced in a 1.5 stage axial compressor. To reveal the effects of this mode on the aerodynamic performance, a three-dimensional numerical simulation was carried out. Three air injection configurations were set to reflect the influence of injected flow velocity and injected mass flow rate. Results show that sloped trench casing treatment combined with air injection could improve the stall margin, total pressure ratio, and adiabatic efficiency of the compressor simultaneously. Moreover, injected flow velocity has a more significant influence on the effectiveness of extending stability than the injected mass flow rate. The optimal configuration obtains the stall margin improvement of 8.37% by using only 0.69% of the whole annulus mass flow rate. Based on a detailed analysis of the rotor flow field, it is found that the high-speed jet causes axial momentum of the incoming flow upstream the rotor blade tip to increase and load of the forepart chord of the rotor blade tip to reduce. The blockage in the tip region of the rotor passage is thus suppressed effectively, which results in the stall margin of the compressor enhanced.

1. Introduction
The compressor/fan design in the modern aero-gas turbine is developing in the direction of high load and high efficiency. The increase of compressor stage load makes the cascade flow more unstable. Studies of flow instability in the compressor have indicated that the flow instability at the rotor tip region is one of the major reasons.
To ensure the stable operating range of the compressor, effective measures are needed to control the rotor tip flow, such as casing treatment, rotor tip air injection and so on. Slotted and grooved casing treatment is the most common. Their effectiveness of extending stability is well while causing the compressor’s efficiency to be sacrificed partly. However, a casing treatment type named sloped trench has the capability of improving the compressor’s efficiency without or slightly sacrificing the stall margin. Wisler and Beacher [1] investigated the effects of geometric parameters of sloped trench casing treatment on the performance and stable operating range of an axial compressor composed of four same stages. Hou et al. [2] studied numerically the effects of sloped trench casing treatment on performance and stability of axial compressor. Results showed that under single-stage environment, the stability was slightly improved as well as the total pressure ratio and efficiency. Generally speaking, the researches on the sloped trench casing treatment is few.
The studies on rotor tip air injection have been performed for many years. Griffin and Koch et al. [3] found that well effectiveness of extending stability was achieved by endwall injection under the condition of inlet distortion. Day [4] experimentally verified the active control of air injection in a low-speed four-stage compressor for the first time. Suder et al. [5] studied the influence of discrete tip injection on the stability of a transonic axial compressor rotor. Wang et al. [6] investigated the effects of circumferential coverage on compressor performance in a transonic axial compressor with discrete tip injection. In recent years, some researchers performed investigations on the measure of cylindrical trench casing treatment combined with air injection. The research of Kim et al. [7,8] showed the optimized cylindrical trench casing treatment combined with air injection could improve the stall margin and peak efficiency of rotor 37 simultaneously. Reza et al. [9] numerically simulated ejecting airflow on the front end of a continuous circumferential groove above the rotor. Results showed that air injection as small as only 0.5% of the mainstream mass flow rate caused the stall margin of the compressor rotor to increase by 15.5%.

Inspired by the above work, this paper designs a new extending stability mode, sloped trench casing treatment combined with air injection. We perform a three-dimensional numerical simulation in a 1.5 stage axial compressor to explore the effects of this mode on the compressor’s performance and stability and to analyze the mechanism.

2. Investigated compressor and description of sloped trench casing treatment combined with air injection

The test case was a 1.5 stage axial compressor composed of an IGV row, a rotor row and a stator row. The blade number of these three rows above was 26, 19, 30, respectively. The tip clearance size of the rotor blade was 0.52% of blade span, and the rotational speed was 5949rpm. The schematic diagram of the compressor model with a sloped trench and jet holes is shown in figure 1. The rotor blade tip was restricted to coincide with the compressor casing baseline. The distance between the front end of the sloped trench and the rotor blade tip was 5% of \( C_{ax} \) which represented the axial chord length of the rotor blade top surface. The rear end of the sloped trench was located directly above the trailing edge of the blade top surface. The circular exit of airflow passages manufactured inside the casing located on the front end of the sloped trench. Its diameter is 1.5mm, slightly smaller than the height of the front end. The airflow was injected in parallel to the trench with no deviation circumferentially.

3. Numerical approach and validation

Numerical simulations were performed utilizing the flow solver EURANUS. The equations were discretized in space using a cell-centered finite volume formulation and in time using an explicit four-stage Runge-Kutta method. To capture the TLV sharply near the casing wall, a second-order upwind scheme based on a flux difference splitting formulation [10] with the Van Albada limiter being implemented was chosen to evaluate the inviscid fluxed. One equation turbulence model of Spalart
and Allmaras was employed to estimate the eddy viscosity. Local time stepping, implicit residual smoothing, and multi-grid techniques were used to reduce the computation cost. A single-passage grid was adopted in the present study. Figure 2 shows the mesh structure of the compressor model with the sloped trench. O4H topology was chosen to model the blade passage, and butterfly topology was used to model the tip gap. IGV, rotor, and stator blade passage consisted of $57 \times 73 \times 101$, $97 \times 89 \times 117$, and $53 \times 73 \times 73$ grid nodes, respectively, in the pitch-wise, spanwise, and streamwise directions. 17 nodes were distributed in the rotor blade tip gap in the spanwise direction. The grid clustering was applied near wall surfaces to guarantee $y^+ \leq 10$.

The boundaries of the solution domain are shown in figure 3. At the inlet boundary, the total pressure, total temperature, and flow angle were imposed. The static pressure was specified at the outlet, and its radial profile was determined based on the radial equilibrium equation. No-slip and no-heat transfer conditions were imposed at solid boundaries. Periodic boundary conditions were used for the single passage domain. The full non-matching mixing plane approach was used for the connection between the rotary and the stationary blocks. Air injection was modeled using source terms that were set to provide the injected mass flow rate. The total temperature of the jet was set to 300K as the same as that of the inlet boundary. In the present investigation, four compressor configurations were simulated, which were marked as SC, ST&Inj20/0.25, ST&Inj10/0.25, and ST&Inj20/0.5. Taking ST&Inj20/0.25 as an example, the first number noted that 20 jet holes were set in one IGV blade passage and the second number noted that the injected mass flow rate was 0.25 kg/s.

Grid independency tests for total pressure ratio and adiabatic efficiency of different compressor configurations have been performed. Figure 4 shows the results of SC and ST&Inj20/0.5 at PEC. Results of ST&Inj20/0.25 and ST&Inj10/0.25 are not presented here because the tendency is similar to ST&Inj20/0.5. It is found that about 325000 grid points is enough for all configurations.

![Figure 2. Mesh structure of the sloped trench casing compressor.](image1)

![Figure 3. Boundary conditions of the solution domain.](image2)

![Figure 4. Grid independency tests for total pressure ratio and adiabatic efficiency at the mass flow condition of SC’s peak efficiency point.](image3)
4. Numerical results and discussion

4.1. Performance characteristics

The total pressure ratio and adiabatic efficiency of four compressor configurations are presented in figure 5. They show that the chock point shifts right slightly while the near stall point shifts left remarkably, which means the stable operating range is improved. Furthermore, the total pressure ratio and adiabatic efficiency of ST&Inj20/0.5 and ST&Inj10/0.25 is higher than that of SC in the latter’s whole operating range. ST&Inj20/0.25 could also improve the total pressure ratio and adiabatic efficiency in most operating range of SC except around NS.

![Characteristics of total pressure ratio](image)

![Characteristics of adiabatic efficiency](image)

Figure 5. Characteristic curves of SC and ST&Inj.

The stall margin improvement is defined by the following formula:

\[
SMI = \left( \frac{m_{SC} - m_{ST&Inj}}{m_{SC}} \right) \times 100\%
\]

Where \( m_{SC} \) and \( m_{ST&Inj} \) refer to the total inlet mass flow rate of SC and ST&Inj configurations.

Compare to ST&Inj20/0.25, in ST&Inj10/0.25, the injected velocity has doubled, and the injected mass flow is kept the same. Compare to ST&Inj20/0.25, in ST&Inj20/0.5, the injected velocity remains unchanged, but the injected mass flow has doubled. However, the SMI of ST&Inj20/0.25, ST&Inj10/0.25, and ST&Inj20/0.5 is 2.39%, 5.23%, and 8.37%, respectively. The facts above mean that the injected velocity has a more significant influence on the effectiveness of extending stability than injected mass flow, which makes obtaining satisfactory stall margin improvement in the cost of as small as external air source become possible.

4.2. The Flow field in the tip region of rotor blades

The meridional entropy production distribution and its enlarged views for the four compressor configurations at NSC are displayed in Figure 6. The partial relative velocity streamlines are also presented in the second enlarged view. It is found that in SC, the loss is mainly concentrated in above about 80% blade span region of the rotor and stator passage, which is caused by the intermixing of tip leakage flow, casing boundary layers and mainstream. In addition, there exists a vortex near the leading edge of the rotor blade tip, resulting in a local high loss. In ST&Inj20/0.25, the jet shifts the vortex downstream slightly, causing the local loss to decrease. Nevertheless, the overall loss of both rotor and stator passage is increased. In ST&Inj10/0.25 and ST&Inj20/0.5, the jet eliminates the vortex, which improves the flow quality of the tip region of the rotor blade passage. As a result, the loss in the rotor blade tip region is considerably decreased, and the loss in the stator blade passage is also slightly declined. These are consistent with the fact shown in Figure 6(a) that at NSC, the efficiency of
ST&Inj10/0.25 and ST&Inj20/0.5 is higher than that of SC, however efficiency of ST&Inj20/0.25 is lower than that of SC.

![Image](image1.png)

**Figure 6.** Meridional entropy production distribution and partial relative velocity streamlines at NSC.

The static pressure isolines and negative axial velocity contours on the rotor blade tip section for the four compressor configurations at NSC are displayed in figure 7. The TLV trajectory is indicated by the solid red line connecting the static pressure groove near the blade suction side. The angle between the TLV trajectory and axial direction is marked at the upper left corner. In SC, the TLV trajectory is almost perpendicular to the axial direction. The interface between TLF and incoming flow is almost parallel to the leading edge plane. Thus, the reverse axial flow nearly blocked the tip region completely. If SC throttles further, the blockage in the tip region of the rotor blade passage will become more serious. Then the rotor will occur to stall first, which will cause the compressor to stall eventually. In ST&Inj20/0.25, the TLV trajectory is deflected about 2° towards the rotor blade suction side. The reverse axial flow region shrinks a little and shifts downstream slightly. Consequently, the blockage in the passage is alleviated partly but severe yet. In ST&Inj10/0.25 and ST&Inj20/0.5, the TLV trajectory is deflected towards the rotor blade suction side by up to 8° and 12° individually. Moreover, the reverse axial flow region is reduced significantly. Therefore, the flow capacity of the passage tip region is enhanced substantially. Besides, from figure 7 (b)(c)(d), it is found that doubling the injected velocity improves the flow capacity of the passage tip region more than doubling the injected mass flow, which is consistent with the effectiveness of extending stability of ST&Inj20/0.25, ST&Inj10/0.25, and ST&Inj20/0.5.

![Image](image2.png)

**Figure 7.** Static pressure isolines and negative axial velocity contours on the rotor blade tip section at NSC.
On the one hand, the high-speed jet introduces additional axial momentum into the tip region of the rotor blade passage. On the other hand, the jet will impinge to the rotor blade pressure side when moving on downstream. This phenomenon changes the static pressure distribution of the rotor blade surface, thereby affecting TLF’s driving force determined by the static pressure difference between the pressure side and suction side of the rotor blade. The two factors above jointly exert an influence on TLV trajectory and blockage level in the tip region of the rotor blade passage. In the following, a detailed analysis will be made in terms of the rotor tip incoming flow’s axial momentum and TLF’s driving force.

Figure 8 shows the chordwise distribution of TLF’s driving force difference between SC and ST&Inj configurations at NSC. The ordinate is normalized by standard atmospheric pressure. Figure 9 depicts the spanwise distribution of the circumferentially mass-averaged axial momentum on IGV/Rotor interface for the four compressor configurations at NSC. The abscissa is normalized by $\rho_{ref} \cdot U_{tip}^2$. $\rho_{ref}$ is the density of mainstream inlet boundary, and $U_{tip}$ is the rotor tip speed. The range of above 100% span is jet area.

Compared to SC, in ST&Inj20/0.25, TLF’s driving force decreases obviously in the range of forpart 7.4% chord length of the rotor blade top surface. However, the axial momentum in the jet area is merely equivalent to that of the mainstream. Thus, the flow field below the front end of the sloped trench is just improved slightly. As a result, the deflection of the TLV trajectory is small, and the decrease of the blockage level in the tip region of the rotor blade passage is low. Compared with ST&Inj20/0.25, in ST&Inj10/0.25, the range where TLF’s driving force decreases enlarges to 11.0% chord length of the rotor blade top surface though the decreased amplitude is basically unchanged. Furthermore, the axial momentum in the jet area increases significantly, which is much higher than that of the mainstream. It is also found that motivated by the high-speed jet, in the area of about 4% blade span below the front end of the sloped trench, the axial momentum is evidently enlarged. Eventually, the deflection of the tip leakage vortex trajectory is obvious, and the blockage level in the tip region of the rotor blade passage improves greatly. Compared to ST&Inj10/0.25, in ST&Inj20/0.5, the range where TLF’s driving force decreases considerably is almost unchanged while the decreased amplitude is nearly doubled. The axial momentum in the jet area also increases, however the variety is relatively small. As to the axial momentum below the front end of the sloped trench, they are almost identical. Consequently, the blockage level in the tip region of the rotor blade passage is improved further. However, it should be noted that the improvement degree is not as good as that of ST&Inj20/0.25 to ST&Inj10/0.25.

**Figure 8.** Chordwise distribution of TLF’s driving force difference between SC and ST&Inj configurations at NSC.

**Figure 9.** Spanwise distribution of the circumferentially mass-averaged axial momentum on IGV/Rotor interface at NSC.
According to the analysis above, it is concluded that the jet brings two benefits. Firstly, the axial momentum of the incoming flow upstream the rotor blade tip is increased. Secondly, the load in the range of the forepart chord length of the rotor blade tip is reduced. As a result, the tendency of TLF developing towards upstream is suppressed, and the blockage in the tip region of the rotor blade passage is improved. Thereby the rotor operating condition is recovered to stable. For these two positive effects, the former plays a major role. In terms of increasing axial momentum of the incoming flow upstream the rotor blade tip, the injected velocity has a more significant effect than that of the injected mass flow, which explains why the injected velocity has a greater influence on the effectiveness of extending stability than the injected mass flow.

5. Conclusions
The main conclusions drawn from the present research work can be summarized as follows:
(1) The measure of sloped trench casing treatment combined with air injection could improve the total pressure ratio, adiabatic efficiency, and stall margin simultaneously. In present study, the optimal configuration obtained the stall margin improvement of 8.37%. At NCC, PEC and NSC, the total pressure ratio was increased by 0.52%, 0.31%, 0.62%, the adiabatic efficiency was increased by 1.67%, 0.75%, 0.57%.
(2) In sloped trench casing compressor with air injection, air injection brought two benefits. The axial momentum of the incoming flow upstream the rotor blade tip was enhanced for one thing, and the load in the forepart chord length of the rotor blade tip was declined for the other. Therefore, the blockage level in the rotor blade tip passage was reduced significantly, which resulted in the compressor’s stall margin being improved.

Nomenclature

- SC: smooth casing compressor
- ST&Inj: sloped trench casing compressor with air injection
- TLV: tip leakage vortex
- TLF: tip leakage flow
- NS: near stall point of SC
- NSC: operating condition with the same inlet mass rate as NS
- PE: peak efficiency point of SC
- PEC: operating condition with the same inlet mass rate as PE
- NC: near chock point of SC
- NCC: operating condition with the same inlet mass rate as NC

References

[1] Wisler D C, Beacher B F. Improved compressor performance using recessed clearance (trenches)[J]. Journal of Propulsion and Power, 1989, 5(4): 469-475.
[2] Hou Jie-xuan, Liu Yang-wei. Study of sloped trench casing treatment on performance and stability of axial compressors[C]// GPPS, Beijing, China, 2019.
[3] Koch C C, Smith L H, Jr. Experimental evaluation of outer case blowing or bleeding of a single stage axial flow compressor, Part VI—Final Report[R]. NASA CR–54592, 1970.
[4] Day, I J. Active suppression of rotating stall and surge in axial compressors[J]. Journal of Turbomachinery, 1993, 115(1): 40-47.
[5] Suder K L, Hathaway M D, Thorp S A, et al. Compressor stability enhancement using discrete tip injection[J]. Journal of Turbomachinery, 2001, 123(1): 14-23.
[6] Wang W, Chu W, Zhang H, et al. Numerical investigation on the effects of circumferential coverage of injection in a transonic compressor with discrete tip injection[C]// ASME Turbo Expo 2014. Düsseldorf, Germany, 2014.
[7] Kim D W, Kim J H and Kim K Y. Parametric study on aerodynamic performance of a transonic axial compressor with a casing groove and tip injection[J]. Applied Mechanics Materials, 2013, 284:872–877.
[8] Kim D W, Kim J H and Kim K Y. Aerodynamic optimization of a transonic axial compressor with a casing groove combined with tip injection[J]. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 2013, 227(8): 869-884.
[9] Reza T Z, Mohammad H A B, Improvement of aerodynamic performance of a low speed axial
compressor rotor blade row through air injection[J], Aerospace Science and Technology, 2018, 72: 409-417.

[10] Roe P L. Approximate riemann solvers, parameter vectors, and difference schemes[J]. Journal of Computational Physics, 1981, 43(2): 357-372.