Effects of Sloped Trench Casing Treatment Combined with Air Injection on Stall Triggering Factor 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 stability, a three-dimensional numerical simulation was carried out. Results show that sloped trench casing treatment combined with air injection could improve the stable operating range, total pressure ratio, and adiabatic efficiency of the compressor simultaneously. The optimal configuration obtains the stable range extension of 26.47% by using only 0.69% of the whole annulus mass flow rate. Based on a comparison of the stall routes, it is found that the smooth casing compressor occurring stall is caused by a blockage cell formed mainly by the low-velocity tip leakage flow. However, the stall of the sloped trench casing compressor with air injection is caused by a considerable blockage cell formed jointly by the low-velocity tip leakage flow and separated flow on the suction surface of the middle-upper span of the rotor blade. The latter's contribution cannot be neglected.

Nomenclature

| SC       | smooth casing compressor | ST&Inj | sloped trench casing compressor with air injection |
|----------|--------------------------|--------|-----------------------------------------------|
| 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 choke point of SC    | NCC    | operating condition with the same inlet mass rate as NC |

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 cylindrical and sloped trench casing treatment on the performance and stable operating range of an axial compressor...
composed of four same stages. Zhu et al. [2] carried out an experimental study on a subsonic rotor with sloped trench casing treatment. Five configurations were designed. Results showed that sloped trench casing treatment could improve efficiency at the expense of partial stall margin. Hou et al. [3] studied the effects of sloped trench casing treatment on performance and stability of axial compressor under both isolated rotor and single-stage environment by numerical method. Results showed that under single-stage environment, the stability was slightly improved as well as the total pressure ratio and efficiency. The author [4] also investigated the effects of sloped trench casing treatment on the tip leakage flow structure in a compressor cascade. The author considered that with the sloped trench casing treatment, the generation mechanism of tip leakage vortex was altered, which caused the performance of the cascade to improve.

The studies on rotor tip air injection have been performed for many years. In the late 1960s, NASA carried out an experimental study on endwall bleed and injection in an axial compressor. Griffin and Koch et al. [5] found that well effectiveness of extending stability was achieved by endwall injection under the condition of inlet distortion. Day [6] experimentally verified the active control of air injection in a low-speed four-stage compressor for the first time. Suder et al. [7] studied the influence of discrete tip injection on the stability of a transonic axial compressor rotor, which involved a range of injection rates and distributions of injectors around the annulus. Wang et al. [8] investigated the effects of circumferential coverage and size of injectors 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. [9,10] 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. [11] 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 reveal the effects on stall triggering factor of the compressor.

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 inlet guide vane (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. While introducing the sloped trench into the casing above the rotor, keep the rotor blade top surface parallel to the trench by extending the blade. In addition, the rotor blade tip was restricted to coincide with the compressor casing baseline. So the tip clearance size of the extended blade was unchanged. The distance between the front end of the sloped trench and the rotor blade tip was 5% of Cax, 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. In this way, the jet was mainly distributed in the gap region and would not cause additional blockage to the mainstream. The schematic diagram of the compressor model with a sloped trench and jet holes is shown in figure 1.
3. Numerical approach and validation

3.1. Numerical schemes
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 tip leakage vortex (TLV) sharply near the casing wall, a second-order upwind scheme based on a flux difference splitting formulation [12] with the Van Albada limiter being implemented was chosen to evaluate the inviscid fluxes. One equation turbulence model of Spalart and Allmaras [13] was employed to estimate the eddy viscosity. Local time stepping, implicit residual smoothing, and multi-grid techniques were used to reduce the computation cost.

3.2. Gridding
A single-passage grid was adopted in the present study. Figure 2 shows the mesh structure of the compressor model with the sloped trench. The distance from the inlet plane to the IGV leading edge was more than 1.5 times of the axial chord length of the IGV top section, and the distances from the outlet plane to the stator blade trailing edge was more than two times of the axial chord length of the stator blade top section. 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 57×73×101, 97×89×117, and 53×73×73 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 $y^+ \leq 10$.

3.3. Boundary conditions
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. All the numerical simulations were started from chock condition and then marched toward the stall point by a gradual increase in the backpressure. When closing to stall, the increment of backpressure was set as 100 Pa. 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 0.25kg/s.

Grid independency tests for total pressure ratio and adiabatic efficiency of different compressor configurations have been performed. Figure 3 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. From figure 5, it is found that the medium mesh is enough for SC and ST&Inj20/0.5 both.

(a) SC (b) ST&Inj20/0.5 

Figure 3. Grid independency tests for total pressure ratio and adiabatic efficiency at the mass flow condition of SC’s peak efficiency point.

4. Numerical results and discussion

4.1. Performance characteristics

The total pressure ratio and adiabatic efficiency of four compressor configurations are presented in figure 4. They show that the choke 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.

(a) Characteristics of total pressure ratio (b) Characteristics of adiabatic efficiency

Figure 4. Characteristic curves of SC and ST&Inj.

The stable range extension is defined by the following formula:

\[
SRE = \left( \frac{\left( \dot{m}_{\text{choke}} - \dot{m}_{\text{stall}} \right)_{\text{ST\&Inj}} - \left( \dot{m}_{\text{choke}} - \dot{m}_{\text{stall}} \right)_{\text{SC}}}{\left( \dot{m}_{\text{choke}} - \dot{m}_{\text{stall}} \right)_{\text{SC}}} \right) \times 100\% \quad (1)
\]
Where $m_{\text{peak}}$, $m_{\text{stall}}$, and $m_{\text{choke}}$ are the mass flow rates at peak efficiency, the stall point, and the choke condition, respectively. 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 SRE of ST&Inj20/0.25, ST&Inj10/0.25, and ST&Inj20/0.5 is 7.79%, 16.69%, and 26.47%, 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 stable operating range extension in the cost of as small as external air source become possible.

4.2. Comparison of the stall routes

In this section, ST&Inj20/0.5 configuration is selected for analysis. Mark the near stall point of ST&Inj20/0.5 as NS$_{\text{inj3}}$ point. The relative Mach number contours of the rotor blade tip section for SC and ST&Inj20/0.5 are as shown in figure 5. When SC operated at NSC, the rotor blade tip section is occupied by a vast low-velocity area, which is formed by the blade suction side flow separation and part of tip leakage flow (TLF). TLV occurs to expand near the leading edge of the neighboring blade pressure side. Downstream the expansion location, the velocity of TLF is initially reduced. When moving on downstream, the velocity of TLF is further declined because of the hindering effect caused by the neighboring blade pressure surface. In ST&Inj20/0.5, motivated by the high-momentum jet, the initial position of flow separation shifts downstream to the trailing edge nearby. In addition, TLV’s trajectory deflects towards the blade suction side, and its expansion position moved downstream to the passage exit nearby. Thus the low-velocity region shrinks significantly. When ST&Inj20/0.5 throttles further to NS$_{\text{inj3}}$ point, the reverse pressure gradient in the passage increases correspondingly. The initial position of flow separation shifts upstream again to about 3/4 chord length location of the rotor blade tip section. Although the TLV trajectory is almost unchanged, the expansion position moves upstream to the middle of the passage. So the rotor blade tip passage is blocked again by the low-velocity cell. However, the blockage level is obviously lower than that shown in figure 5(a). The stall of ST&Inj20/0.5 configuration needs to be further explained.

![Figure 5. Relative Mach number contours of the rotor blade tip section.](image)

Figures 6 and 7 depict the spanwise distribution of the diffusion factor and the inlet relative flow angle of the rotor for SC and ST&Inj20/0.5 individually. The diffusion factor is defined as:

$$DF = 1 - \frac{W_{\text{out},r}}{W_{\text{m},r}} + \frac{W_{\theta,r}}{2\sigma W_{\text{m},r}} \tag{2}$$

Where $W_{\text{out},r}$, $W_{\text{m},r}$, $W_{\theta,r}$ refer to mass-averaged rotor relative exit, inlet, and tangential velocity, respectively, and $\sigma$ is rotor tip solidity. Compared to SC, for ST&Inj20/0.5 at NSC, the diffusion factor above 82.5% span is declined with the residual span being increased. The inlet relative flow angle
above 96% span is decreased with the residual span being increased. When ST&Inj20/0.5 throttles to NS inj3 point, the diffusion factor is almost increased on the full span, the inlet relative flow angle is also increased on the full span except the span effected by the jet. These mean the load-carrying limit of the rotor is enhanced in ST&Inj20/0.5.

Figure 6. Spanwise distribution of the diffusion factor of the rotor.

Figure 7. Spanwise distribution of the inlet relative flow angle of the rotor.

Figure 8 displays the iso-surface of relative Mach number equal to 0.2 and part of relative velocity streamlines in the rotor passage for SC and ST&Inj20/0.5. The enclosing iso-surface in the passage represents the blockage cell, the streamlines colored by red indicate the TLF, and the streamlines colored by blue indicate the separated flow. It is clearly shown that the blockage cell includes two parts. One is the low-velocity TLF, and the other is the separated flow. It should be pointed out that in SC the low-velocity cell is mainly formed by the TLF, the contribution of separated flow is fairly minor. Compared to SC, for ST&Inj20/0.5 at NSC, the redistribution of the load and inlet relative flow angle along the blade span makes the contribution rate of separated flow and TLF on blockage cell changed. The span range with separation below the rotor blade tip is enlarged, however the low-velocity region formed by TLF shrinks. When ST&Inj20/0.5 throttles to NS inj3 point, the separation extends to the midspan, causing the radial and circumferential dimension of the blockage cell to broaden significantly. As a result, the rotor passage is blocked severely, much more than that of SC at NSC. If ST&Inj20/0.5 continues to throttle, the rotor will stall first, causing the compressor finally to fall into stall.

5. Conclusions
Aerodynamic performance of a 1.5 stages axial compressor was improved via a new extending stability mode, sloped trench casing treatment combined with air injection. 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 stable operating range simultaneously. In present study, the optimal configuration obtained the stable range extension of 26.47%. 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. The measure of sloped trench casing treatment combined with air injection raised the load-carrying limit of almost the full rotor blade span. Thus, the tendency of flow separation on the blade suction surface of the middle and upper span of the rotor was increased. The blockage cell almost formed by the low-velocity TLF gave rise to the smooth casing compressor occurring stall. However, the stall of sloped trench casing compressor with air injection was caused by the large dimensional blockage cell, which was jointly formed by the flow separation on the upper-middle span of the rotor blade and the low-velocity TLF.

References

[1] D H, Beacher B F. Improved compressor performance using recessed clearance (trenches)[J]. Journal of Propulsion and Power, 1989, 5(4): 469-475.

[2] Zhu Jun-qiang, Zhao Yi, Liu Zhi-wei. An experimental investigation on treatment of compressor casing with skew grooves[J]. Journal of Aerospace Power, 1998, 13(1): 23-26. (in Chinese)

[3] Hou Jie-xuan, Liu Yang-wei. Study of sloped trench casing treatment on performance and stability of axial compressors[C]// Proceedings of Global Power and Propulsion Society, Beijing, China, 2019.

[4] Hou Jie-xuan, Liu Yang-wei, Lu Li-peng. Effects of sloped trench casing treatment on compressor cascade[J]. Journal of engineering thermophysics, 2019, 40(9): 1997-2003. (in Chinese)

[5] Bailey E E, Voit C H. Some observations of effects of porous casings on operating range of a single axial-flow compressor rotor[R]. NASA TM-X-2120, 1970.

[6] Day, I J. Active suppression of rotating stall and surge in axial compressors[J]. Journal of Turbomachinery, 1993, 115(1): 40-47.

[7] 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.

[8] Wang W, Chu W, Zhang H. The effect of injector size on compressor performance in transonic axial compressor with discrete tip injection[J]. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 2014, 228(7): 760-771.

[9] 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.

[10] 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.

[11] 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.

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

[13] Spalart P, Allmaras S. A one-equation turbulence model for aerodynamic flows[J]. Recherche Aerospatiale, 1994, 1(1): 5-21.