Global Power & Propulsion Society

Proceedings of Global Power and Propulsion Society
ISSN-Nr: 2504-4400
GPPS Hong Kong 2023
October 17-19, 2023
www.gpps.global

GPPS-TC-2023-295

Effect of Rotor with Tip Ring on Supersonic Fan Performance

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ABSTRACT

Rotor with tip ring can suppress blade flutter, and has significant effect on the flow structure and fan performance with increase of the rotor inlet relative Mach number. The mechanism of rotor with tip ring on the fan performance at designed rotation speed is investigated using three dimensional simulation of a two stage highly loaded fan model. The effect of bowed blade stacking and skewed tip ring on the fan performance is evaluated. Numerical results show that the second rotor with tip ring results in a large separation at tip corner flow, leading to decrease of the fan pressure ratio and efficiency, and the surge margin declining from 20.8% to 10.6%. When the second rotor is modified with positive bowed blade stacking and the tip ring is skewed, the separation flow is successfully suppressed for all cases at designed rotation speed and the surge margin restores to 17.0%. The improvement effect of the positive bowed blade stacking and skewed tip ring for the supersonic fan performance is confirmed, which could be used for the highly loaded fan rotor design of FLADE.

INTRODUCTION

Fewer stages and higher loads are the eternal pursuit of compressor aerodynamic design. It is also an important development direction for the thrust-weight ratio promotion of aero-engine. As the averaged stage load of fan/compressor keeps increasing, the rotor inlet relative Mach number becomes higher. It gives rise to the strong interactions between shock waves/boundary layer and tip leakage vortex at the rotor tip region (Chima, 1998; Hoeger et al., 1999; Xie et al., 2012), leading to the boundary layer separation or leakage vortex breakdown. It results in a substantial increase in compressor flow loss and becomes one of the main factors that limit the stability and efficiency of fan/compressor.

The design of highly loaded blade can be divided into three periods in the fan/compressor performance improvement process, which include straight blade, twisted blade and bowed/swept blade (Liu et al., 2015; Zhang et al., 2021). The resulting composite bowed/swept technology (Ji et al., 2005*a*,*b*; Wang et al., 1990) has been widely used in modern turbomachinery design. In the design of highly loaded fan/compressor, forward-swept blade design can reduce tip shock intensity and improve efficiency and surge margin. Hah et al. (1998) analyzed the influence of rotor sweep on the shock wave structure in supersonic cascade flow, and found that when the forward-swept blade was adopted, the low-energy flow in boundary layer left the blade surface in the middle blade height, and the shock wave in the tip region moved downstream, which widened the compressor's surge margin. Yang and Shan (2009) compared the effects of forward sweep and backward sweep on the performance of a single-stage fan rotor. It was found that the vortex structure induced by tip clearance flow in a forward-swept rotor was stronger, which resulted in the efficiency reduction of about 1%. While the shock position in the forward-swept rotor was more downstream, and the surge margin was improved by about 3% compared with that in backward-swept one. Mao et al. (2015) optimized the distribution of Stage-35 blade stacking line in circumferential (bowed) and meridional (swept) direction. The results showed that the forward-swept design improved the flow near the tip and root of blade, and promoted the shock wave on the whole blade height to move downstream, which increased the efficiency by about 0.9% at the design condition. Wang et al. (1991) pointed out that in conventional cascades, the pressure gradient along the blade height caused the boundary layer on the suction surface to migrate to the blade root and confluent with the boundary layer on the hub wall, resulting in the thickening of the boundary layer on the hub endwall. It was easy to trigger flow separation. The circumferential curved (bowed) blade design proposed by the author changed the pressure distribution on the blade surface and presented a C-shaped distribution, which promoted the boundary layer at the endwall to move to the middle of blade, effectively inhibited radial secondary flow, and reduced the flow loss. It had been widely verified in fan/compressor and turbine blade design. An et al. (2002) compared 10 different bending and tilting configurations for turbine guide vanes in a large expansion tunnel, and confirmed the effectiveness of positive bending and tilting blades in reducing flow loss. Yang and Cao (2020) further analyzed the effect of positive/reverse bowed blade on the flow and performance of a single stage of highly loaded cascade using an arc stacking line. Positive bowed blade formed C-shaped static pressure distribution on the blade suction surface, which promoted the boundary layer migrating form endwall to blade middle, effectively inhibited corner separation. However, positive bowed design increased the load of the blade middle region, which could induce flow separation.

The introduction of forward swept design for supersonic rotor improved the shock distribution characteristics of the cascade flow and increased the fan/compressor efficiency and stable operating margin. However, the swept blade adapted to high inlet Mach number was generally thin and protruding, resulting in significant weakening of local blade rigidity and more prone to vibration and flutter (Wu et al., 2012, 2014). In order to improve the vibration problem of swept rotor, the forward-swept fan (XTL87) adopted a carbon fiber tip-ring structure, which avoided the blade flutter and improved the strength (Cao et al., 2013). Zhou et al. (2007) carried out a study on a highly loaded two-stage fan with designed pressure ratio of 4.3 based on the crowned rotor design. It successfully eliminated the risk of rotor vibration. Nevertheless, the crowned blade affected the shock structure and caused flow blockage in the rotor cascade, leading to the fan performance reduction. A similar result with an increased flow loss at the tip region of the crowned rotor was observed in the numerical study of a planar cascade (Ma, 2016), while its impact on the overall performance of subsonic compressor was not significant (Xu, 2018). Compared with subsonic cascade flow, the effect of the crowned rotor on supersonic fan/compressor flow was more important. In addition, the variable cycle engine introduced a third bypass duct to enable the engine to have more flexible bypass ratio regulation, as shown in Fig.1 (chao Zheng et al., 2017). In which, FLADE (fan on blade) configuration was an important component of the third bypass duct for engine regulation. The connected main fan blade formed a typical crowned rotor (rotor with tip-ring), and its aerodynamic performance and operating characteristics had an important effect on the engine stable operation and mode transition.

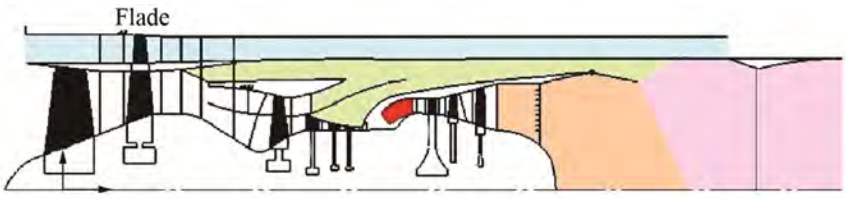

Figure 1 Configuration of an adaptive cycle engine with FLADE (chao Zheng et al., 2017)

Therefore, the present study aims to reveal the mechanism and effect of rotor with tip ring on the supersonic fan performance, and evaluate the effectiveness of the modification with bowed blade stacking and skewed tip ring for fan performance improvement.

METHODOLOGY

A two-stage highly loaded fan model with guide vane as shown in Fig.2, is adopted in this study to evaluate the effect of the second rotor (R2) with tip ring on the fan performance. When the second rotor (R2) is crowned, the clearance between the blade and the shroud is vanished, and the shroud wall rotates together with R2. It is called rotor with tip ring. The grid distribution of the endwall around the blade tip for R2 with gap and tip ring condition is shown in Fig.3. The dimensionless parameter y^+ corresponding to the first layer of wall mesh scale is between 1 and 5.

The NUMECA software is used to solve the three-dimensional Reynolds Averaged Navier-Stokes equations based on the ideal gas and Spalart-Allmaras turbulence model. The second order central difference coupled artificial viscosity is used to capture the shock waves, and the central difference is used to calculate the viscous flux, in which the variable gradient at interface is directly calculated based on the values of adjacent grid cells. The mixing plane model based on the conservative coupling by pitchwise row is selected for the rotor-stator interface. The four-order Runge-Kutta method is used to advance the local time, and the three-layer multi-grid and implicit residual smoothing techniques are used to accelerate the convergence. During calculation, the total temperature and pressure of the inflow at the model inlet are specified as 288.15 K and 101325 Pa, respectively. The averaged static pressure (p_b) at the outlet of the calculation domain is adopted, and the other parameters are zero-order extrapolated.

Figure 2 Two-stage highly loaded Fan model

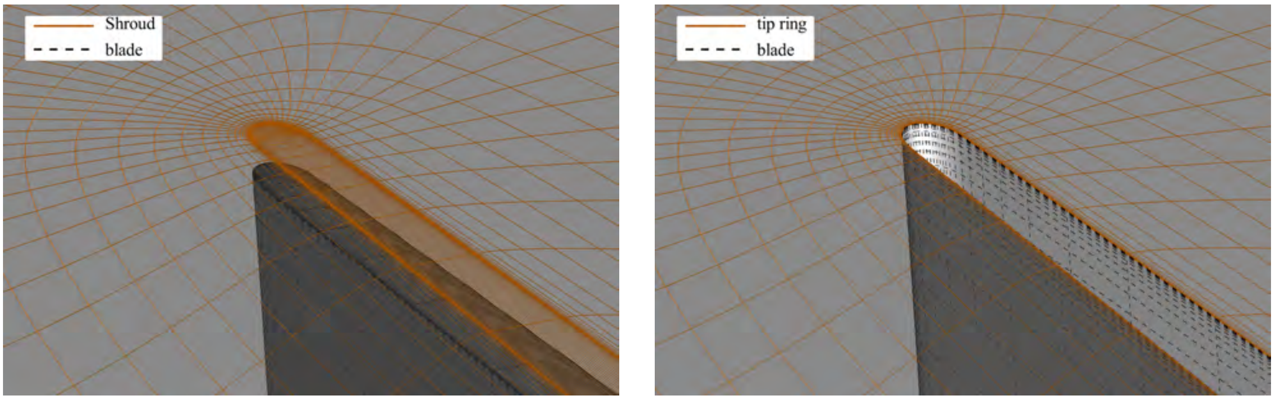

Figure 3 Wall grid in R2 tip region: Left-R2 with gap, Right-R2 with tip ring

RESULTS AND DISCUSSION

Model verification

The performance of the original two-stage fan (Gap) at the designed rotation speed is obtained as shown in Fig.4 by adjusting the averaged outlet pressure (p_b). It is found that the predicted performance is in good agreement with the experimental data. The difference of mass flow rate at working point is within 0.3%, and the maximum efficiency difference is within 0.7%.

According to the definition of compressor Surge Margin (SM),

$$SM = \left[\frac{(\pi/m)_s}{(\pi/m)_d} - 1 \right] \times 100\% \tag{1}$$

where, π and m represent the compressor total pressure ratio and the inlet mass flow rate, respectively. The subscript s and d represent the surge and working point conditions. The stable operating margin of the two-stage fan is 20.8%.

Effect of second rotor with tip ring on fan performance

The predicted performance of the two-stage fan model with second rotor crowned (nogap-O) at designed rotation speed is shown in Fig.5. It shows that the second rotor with tip ring significantly affects the supersonic fan performance, resulting in the maximum total pressure ratio and efficiency decreasing by 8.9% and 2.0%, respectively. The stable working margin is reduced to 10.6%. The rotor with tip ring deteriorates the performance of supersonic fan, which is much more significant than that in subsonic compressor (Xu, 2018).

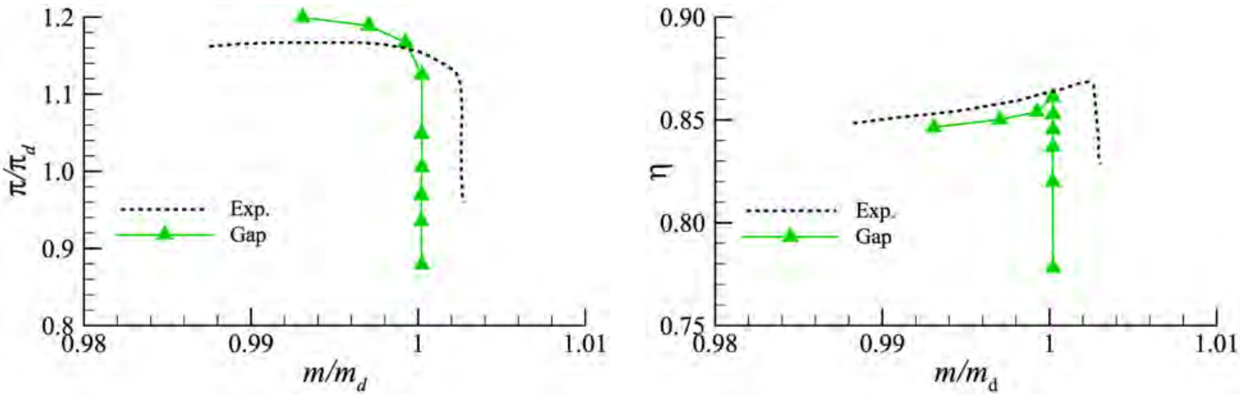

Figure 4 Predicted and experimental performance characteristics of two stage fan: Left-total pressure ratio, Right-adiabatic efficiency

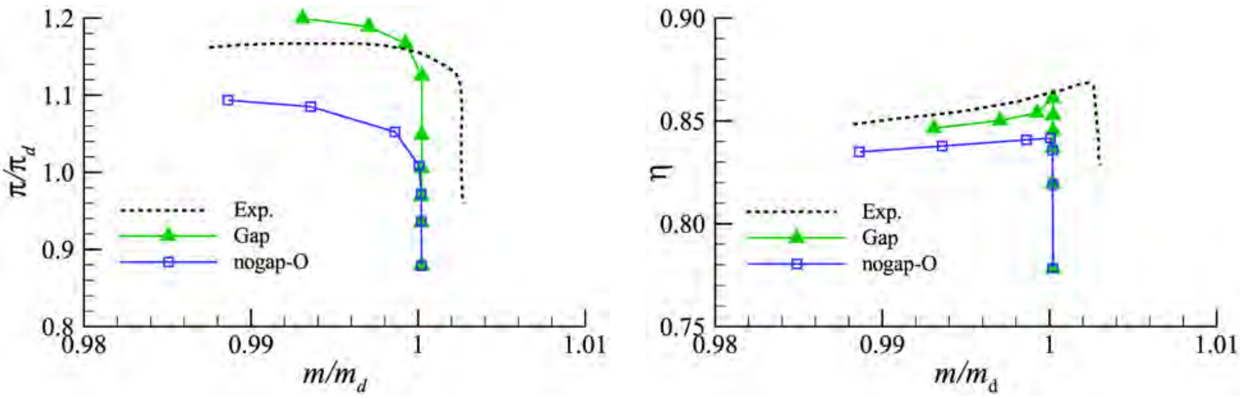

Figure 5 Predicted performance characteristics for second rotor with tip ring (nogap-O): Left-total pressure ratio, Right-adiabatic efficiency

Figure 6 presents the detailed flow structures of the second rotor with gap and with tip ring conditions at the total pressure ratio of π/π_d = 1.05. It is near the design point, which is selected as a higher value than the working point for widening the stable working margin. The gray isosurface of w_z= -3.4 m/s is used to mark the separation flow around the shroud endwall. The blade suction surface is colored by static pressure ratio ($p/p_{t\infty}$) and the friction lines show the flow direction on the blade surface. It is found that there are three separation zones in the blade tip region at the rotor with gap condition (Gap). Where the separation ① is induced by the normal shock interacting with the blade pressure surface boundary layer and occupies about 25% blade height. The separation ② is located at the trailing edge of the suction surface, which is formed by the shock wave/boundary layer interaction and the radial secondary flow. The separation ③ is the leakage flow in the tip clearance originating from the separation ①, which occupies about 1.5% blade height. However, a large separation zone labeled as ③ is formed between the blade suction surface and the shroud endwall at the rotor with tip ring condition (nogap-O), which occupies about 11.5% blade height. It can also be seen from the friction lines distribution on the blade suction surface. It also appears a large separation zone ② originating from the blade leading edge near the hub endwall. However, the separation ① induced by the normal shock interacting with the blade pressure surface boundary layer becomes smaller and located at the middle blade. The separation zones severely block the cascade and reduce the stable working margin.

As shown in Fig.7, the relative inlet Mach number at the blade tip is decreased when the rotor is crowned, causing that the boundary layer near the shroud wall easier to separate after interacting with shock waves. It is also the reason why the rotor with tip ring has a much more significant effect on the performance of supersonic compressor than subsonic one. Meanwhile, the relative Mach number at the blade root is also decreased, leading to boundary layer separation.

The relative Mach number distribution at 95% span section is further compared as shown in Fig.8, in which the black solid contour line of w_z= -3.4 m/s marks the separation zone labeled as ①, ② and ③. It shows that the separated flow ③ caused by the second crowned rotor blocks the cascade and affects the upstream flow, resulting in the normal shock moving upstream in the first rotor cascade. It can be seen more clearly from the pressure distribution on the blade surface as shown in Fig.9. As a result, the load of the first rotor is enhanced with the total pressure ratio increased by 8.8%. The total pressure ratio of the second rotor is reduced by 7.7% according to the separated flow around the blade suction surface.

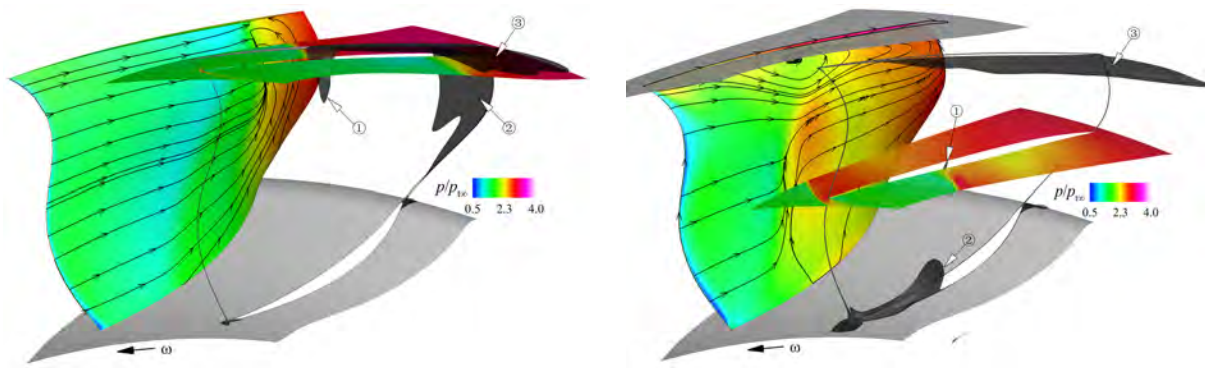

Figure 6 Cascade flow structures in second rotor tunnel: Left-R2 with gap, Right-R2 with tip ring (nogap-O)

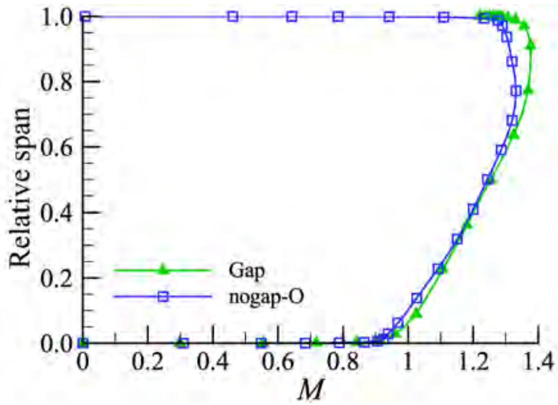

Figure 7 Axisymmetric averaged relative Mach number spanwise distributions at second rotor inlet

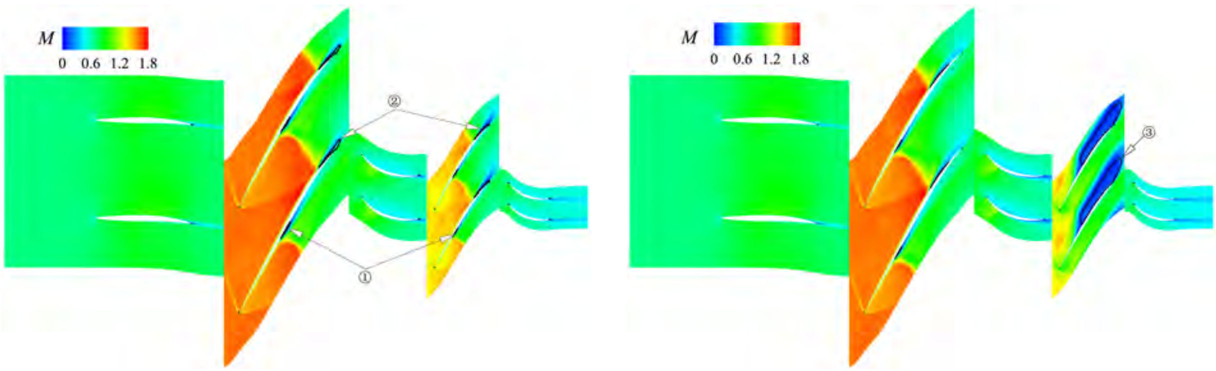

Figure 8 Relative Mach number distribution at 95% span section: Left-R2 with gap, Right-R2 with tip ring (nogap-O)

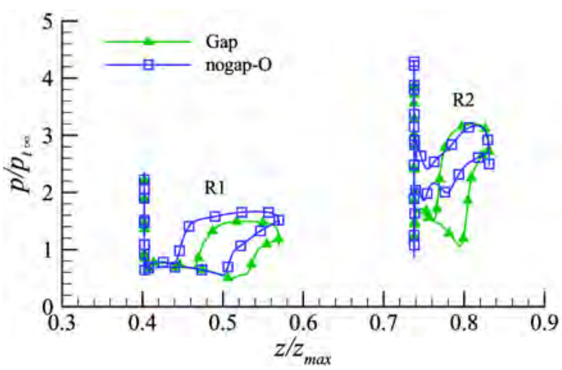

Figure 9 Blade-surface pressure distributions at 95% span section

Improvement on second rotor with tip ring

The flow separation in the tip region at the rotor with tip ring condition is mainly caused by the interaction between shock wave and boundary layer of shroud wall. It leads to the cascade blockage and mass flow rate reduction. Previous study about the effect of circumferential bowed blade stacking line on cascade flow showed that positive bowed blade could induce the suction surface to form a static pressure distribution with low value at middle and high value at ends, which effectively improved the flow near the endwall and inhibits separation (Yang and Cao, 2020). Therefore, the stacking line of second rotor blade is adjusted to a positive bowed distribution as shown in the left of Fig.10. Meanwhile, the crowned shroud wall of the second rotor is skewed locally for adapting to the adjustment of stacking line and improving the cascade flow capacity. The modified crowned second rotor blade is shown in the right of Fig.10.

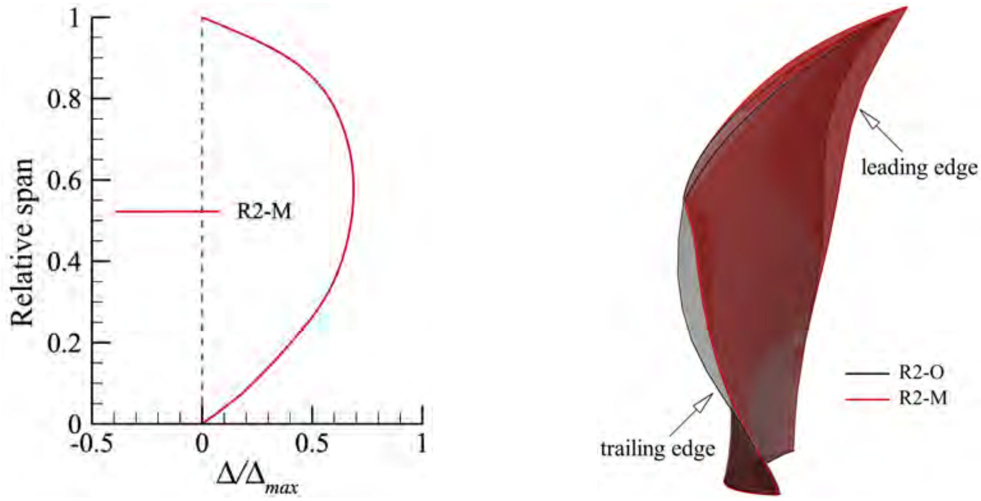

Figure 10 Second rotor blade modified with positive bowed stacking and skewed tip ring: Left-bowed stacking line, Right-blade comparison

Figure 11 shows the performance of the two-stage fan with modified crowned second rotor (nogap-M) at designed rotation speed. It is found that the total pressure ratio is increased effectively at the same mass flow rate, and the efficiency almost restores to the working state of the Gap condition. Compared with the original crowned condition (nogap-O), the efficiency at the working point is improved by 0.9%, and the stable working margin is increased to 17.0%.

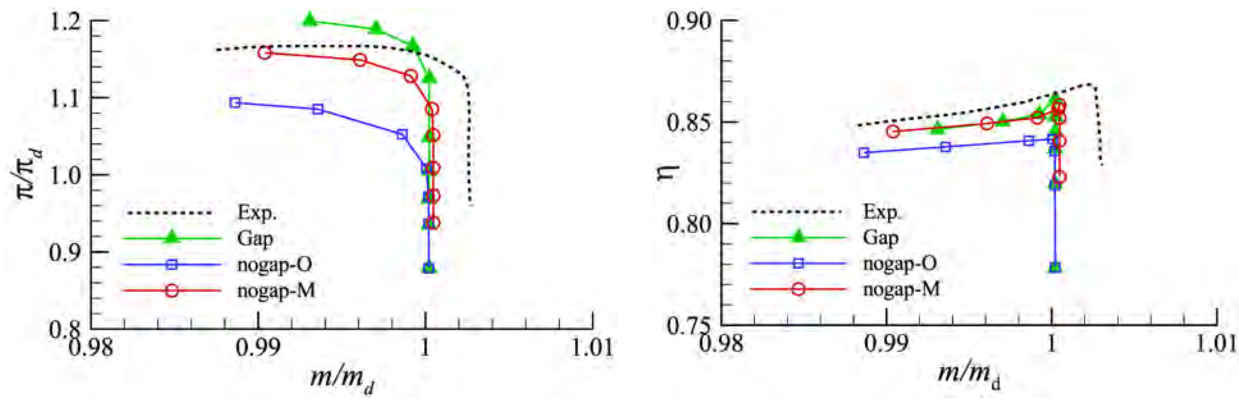

Figure 11 Predicted performance characteristics for modified second rotor with tip ring (nogap-M): Left-total pressure ratio, Right-adiabatic efficiency

The detailed flow structures for the modified crowned rotor at the condition with $\pi/\pi_d = 1.05$ is shown in Fig.12. The separation flow in the second rotor cascade is significantly reduced with the separation ③ occupying 5% blade height and separation ② almost disappearing. According to the relative Mach number (Fig.12-right) and blade surface pressure distributions at 95% span section (Fig.13), the shock wave in the first rotor cascade returns to the position of Gap condition, and the pressure distribution on blade surface basically coincides. The shock wave in the second rotor cascade moves a little forward, but the load is almost consistent with the total pressure ratio changing no more than 0.2%. It is confirmed the effectiveness of the positive bowed stacking and skewed tip ring for improving the performance of supersonic fan with crowned rotor in FLADE design.

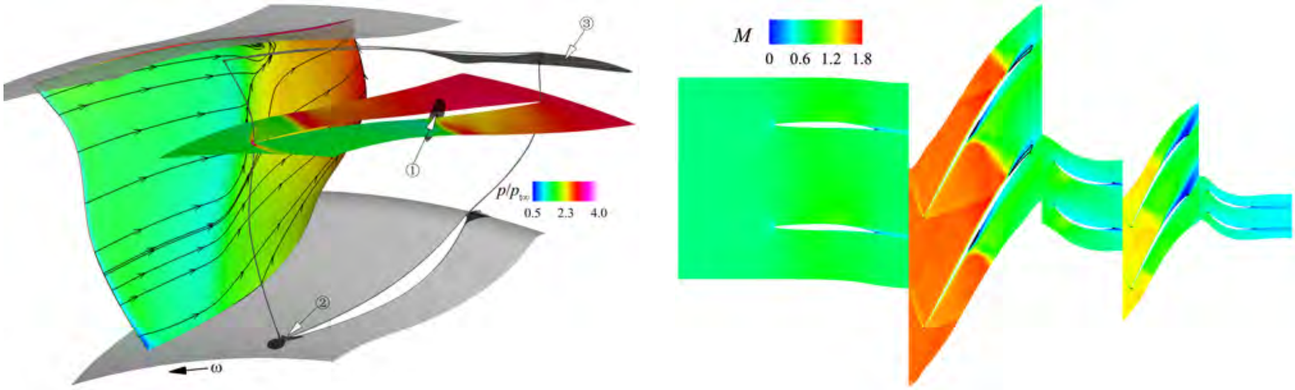

Figure 12 Flow structures for modified second rotor with tip ring (nogap-M): Left-separation flow structure, Right-relative Mach number distribution at 95% span section

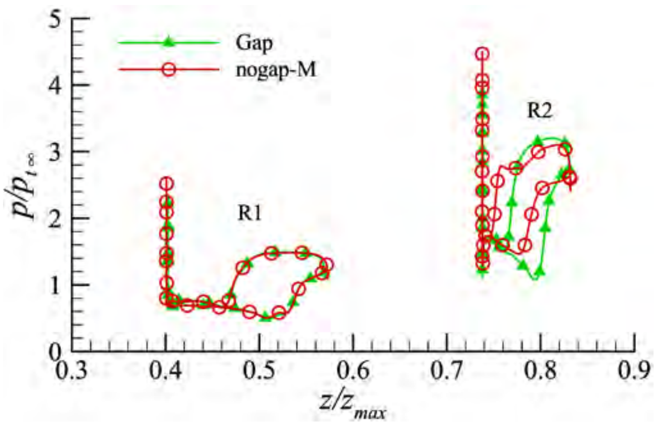

Figure 13 Blade-surface pressure distributions at 95% span section

Flow characteristics of choke and near surge points

It is also evaluated the improvement effect of the modified crowned rotor on the fan performance when it works at different points (choke point and near surge point). It is focused on the flow characteristics at the tip region of the three considered configurations (Gap, nogap-O, and nogap-M). The relative Mach number distribution at 95% span section for different conditions is shown in Fig.14, Fig.15 and Fig.16.

It is found that when the fan with Gap configuration works at choke point, the normal shock waves of the rotor cascades are located at the downstream of the channel. With the increase of outlet static pressure, the fan is close to the surge point, and the normal shock waves in the first and second rotor cascades are pushed to the vicinity of the blade leading edge. At these two operating points, the flow separation zone in the cascade is small as shown in Fig.14.

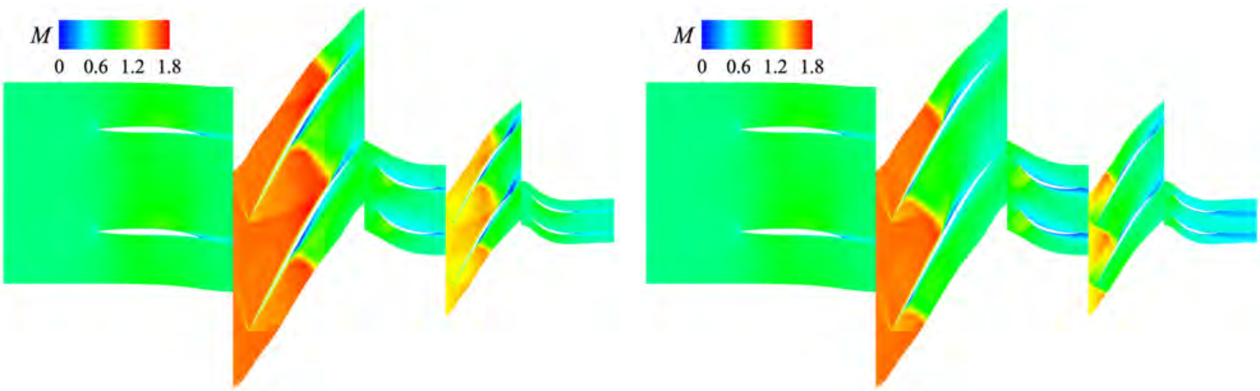

Figure 14 Relative Mach number distribution at 95% span section (Gap): Left-choke point (π/π_d = 0.935), Right-near surge point (π/π_d = 1.200)

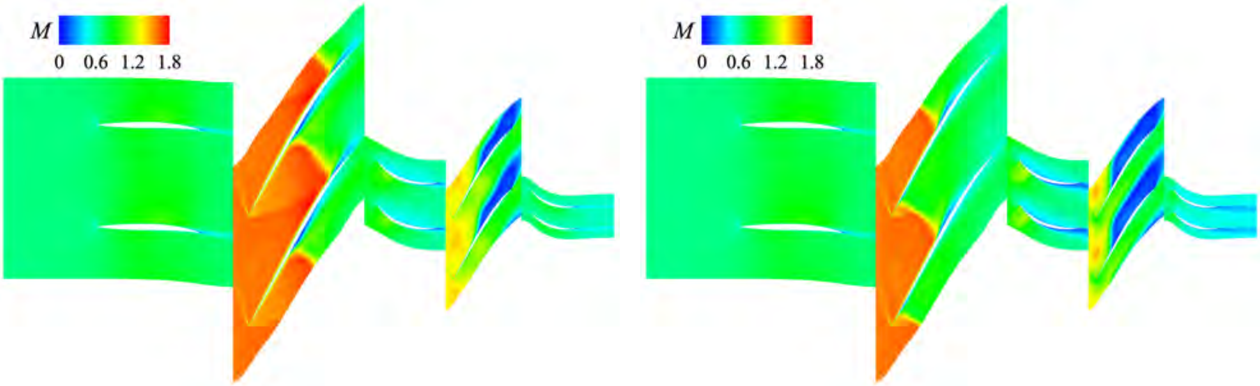

Figure 15 Relative Mach number distribution at 95% span section (nogap-O): Left-choke point (π/π_d = 0.937), Right-near surge point (π/π_d = 1.093)

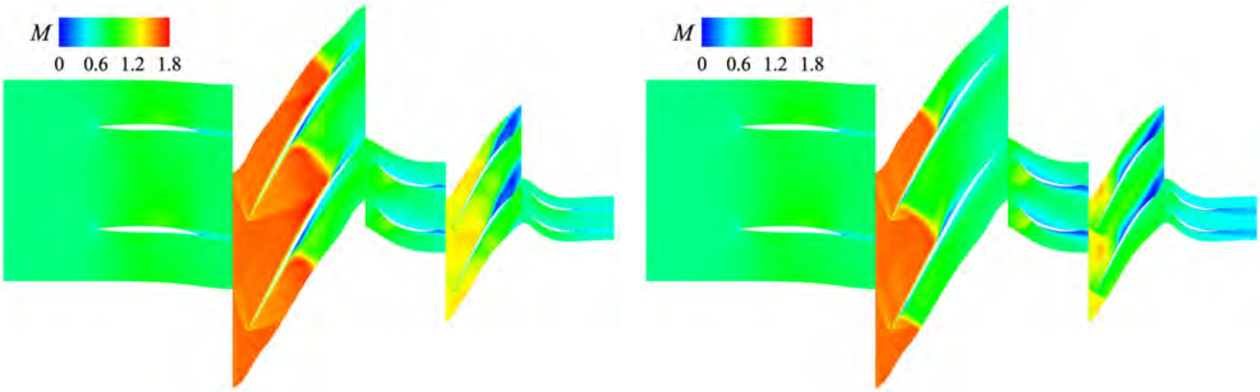

Figure 16 Relative Mach number distribution at 95% span section (nogap-M): Left-choke point (π/π_d = 0.938), Right-near surge point (π/π_d = 1.158)

When the second rotor is crowned (nogap-O), a large separation zone appears in the second rotor cascade at both choke and near surge points. It can occupy 50% of the cascade width. With increase of the outlet static pressure, the separation zone enlarges and moves upstream, as shown in Fig.15, resulting in the maximum fan pressure ratio reduced by 8.9% of that in Gap configuration. For the modified crowned rotor (nogap-M), although separation zones still exist in the rotor cascade at these two operating points, the size of the separation zone is significantly reduced as shown in Fig.16. The maximum fan pressure ratio restores to 96.5% of that in Gap configuration. In summary, the modified crowned rotor with positive bowed stacking and skewed tip ring, can effectively suppress the separation flow in the tip endwall region, and improve the fan performance in the whole working range from the choke point to the near surge point.

CONCLUSIONS

The effect of crowned rotor on the fan performance is significantly different in supersonic and subsonic conditions. The influence of the second rotor with tip ring on the fan performance at designed rotation speed is numerically analysed based on a highly loaded two-stage supersonic fan model. It is also explored the improvement effect of blade stacking line and tip ring profile on the crowned rotor performance. The main results are as follows:

(1) The inlet relative Mach number near the tip ring is decreased in the crowned rotor cascade. As a result the boundary layer flow is separated after interacting with shock waves. The separation flow blocks the cascade and further changes the rotor loads. It seriously deteriorates the fan performance, resulting in the maximum total pressure ratio and efficiency decreasing by 8.9% and 2.0%, respectively. The stable working margin is reduced to 10.6%.

(2) A combination of positive bowed blade stacking line and skewed tip ring profile is adopted on the second crowned rotor, which effectively inhibits the separation flow in the tip endwall region, and improves the fan performance. The maximum fan pressure ratio restores to 96.5% of that in Gap configuration, and the efficiency nearly recovers to the same state and the surge margin is increased to 17%.

(3) The improvement modification for the crowned rotor with above method is only verified on the second rotor at low inlet Mach number. For the first rotor with higher inlet Mach number, there is more serious shock wave/boundary layer interaction at the tip endwall region, which is much easier to lead to the boundary layer separation. Therefore, the further analysis of crowned rotor at higher inlet Mach number will be considered for the FLADE rotor design.

ACKNOWLEDGMENTS

The research was sponsored by Foundation Strengthening Program of National Defense Science and Technology, National Science Foundation of China (No. 12172298) and Sichuan Science and Technology Program (No.2023NSFSC1333).

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