Aerodynamic Performance of Single-Stage Transonic Axial Compressor with Multi-Bleed Airflow

Tuong-Linh Nha, Van-Hoang Nguyen, Xuan-Truong Le, and Cong-Truong Dinh

Abstract Bleeding air in the axial compressor is a well-known method to take air for cooling treatment in the turbine and provide an atmosphere in the cabin. A most common bleed system which is used in gas turbine engine frequently reduce the efficiency and stall margin of the compressor. This study proposes a new bleed air method, the multi-bleed air method, which is enhanced the efficiency and stall margin of the compressor. The multi-bleed air method contains 36 bleed air channels on the rotor domain's shroud surface. The bleeding system is studied using three different bleed types: single-bleed, double-bleed, and triple-bleed in a single-stage transonic axial compressor, NASA Stage 37. The numerical results demonstrated that the aerodynamic performance of a single-stage transonic axial compressor was improved with the multi-bleed method, including total pressure ratio, adiabatic efficiency, and stall margin compared to the smooth casing case. In addition, the adiabatic efficiency and stall margin increase more in the double-bleed case than in single-bleed and triple-bleed cases.

Keywords Single-stage transonic axial compressor · Multi-bleed · 3D-RANS

1 Introduction

The tip leakage vortices and their airflow trajectories are the primary sources of aerodynamic performance reduction in axial compressors. Many experimental and numerical studies have been performed to reduce compressor performance reduction. As for the bleeding airflow, a new casing configuration is investigated by Koch and Smith [1], where the airflow is bled from the shroud surface of an axial compressor

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rotor with a 30° bleeding angle of the flow direction to improve the stall range as compared to the smooth casing by reducing the accumulation of endwall blockage. A passive control method of endwall blockage was investigated by Hathaway [2], and the best bleeding positions were between the start of tip leakage flow (40% of rotor chord length) and further blockage aft of leakage (80% of rotor chord length). The effects of axisymmetric bleed slot position on rotor and stator shroud surface in a single-stage subsonic axial compressor were presented by Wellborn and Michael [3], in which the rotor tip bleed position was most effective near the leading and trailing edges. A bleeding air system on a shroud surface downstream of a rotor in a multistage axial compressor of a gas turbine engine was investigated by Ress et al. [4]. The bleedin]g air system with a 3% bleed rate reduced the separated region near the suction surface of the rotor to increase by 1% in efficiency and 5% in stall margin. Dinh et al. [5, 6] presented the effects and optimization of rotor bleeding airflow on aerodynamic performances of a single-stage transonic axial compressor.

In this work, multi-bleed airflow from the rotor shroud surface through 36 bleed air channels and its geometrical design were performed to determine the effect of bleeding airflow on the aerodynamic performance and stability.

2 Numerical Analysis

2.1 Description of Geometry

To investigate the influences of multi-bleed casing treatments on the aerodynamic performance of the high-speed axial compressor, the transonic axial compressor, NASA Stage 37, was used in this study. The design values of the overall parameters and detailed specifications for NASA Stage 37 were performed by Reid and Moore [7].

Figure 1 illustrates the designs and position of multi-bleed casing treatment in NASA Stage 37. Three different types of bleeding channels along the shroud surface of the rotor domain are presented as “Single-Bleed”, “Double-Bleed”, and “Triple-Bleed”, as shown in Fig. 1c.

2.2 Numerical Method

For the aerodynamic analysis, ANSYS CFX 19.1® [8] was employed to solve the three-dimensional (3D) RANS equations. As illustrated in Fig. 2, the grid systems contain three regions: rotor, stator, and Multi-Bleed. For steady-state simulation, the boundary condition of the stator outlet was defined as an average static pressure. At the rotor inlet boundary, the turbulence intensity and static frame total temperature were set at 5% and 288.15 K, respectively. No-slip wall, smooth wall, and adiabatic

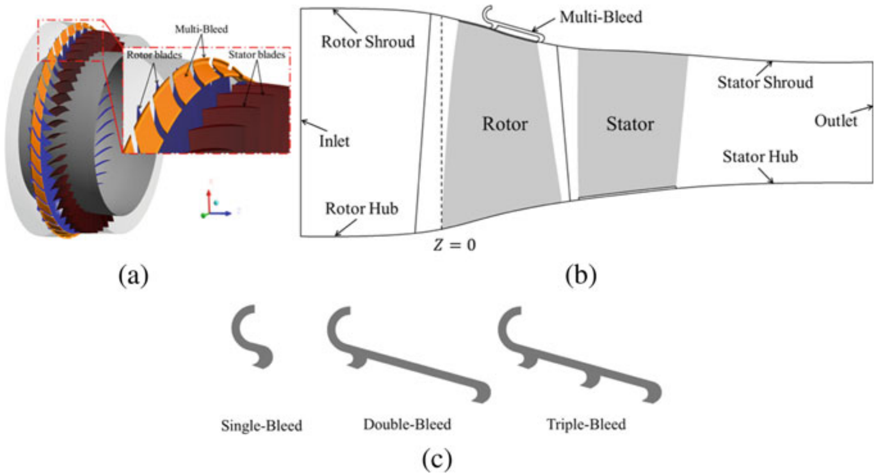

Fig. 1 Geometry of NASA stage 37 with the multi-bleed: **a** 3D view, **b** meridional view, **c** different types of bleeding channels

were applied to the wall surfaces. For the analysis of the stability and performance of the transonic axial compressor: total pressure ratio (PR), adiabatic efficiency (η), stall margin (SM), and stable range extension (SRE) [5, 6] were used to evaluate.

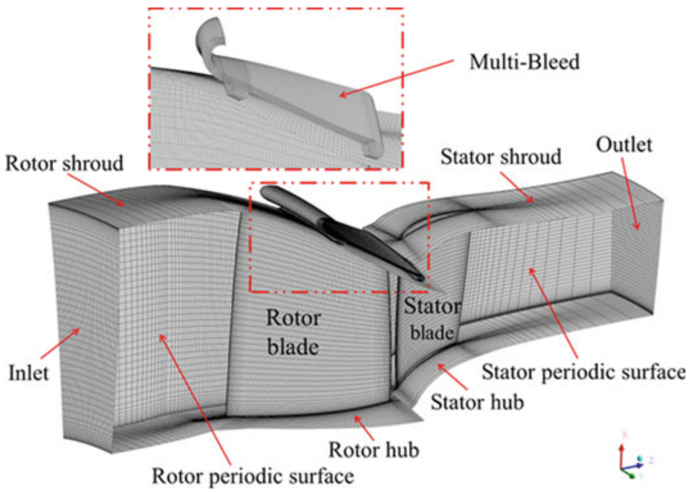

Fig. 2 Computational domain and mesh structure

Table 1 Grid dependency test of NASA Stage 37

	Mesh 1	Mesh 2	Mesh 3
Grid number ($\times 10^6$)	0.34	0.59	0.91
SM	9.30	9.95	9.99
Deviation of SM (%)	6.99	0.40	–
$\dot{m}_{choke}$	20.96	20.98	20.99
Deviation of $\dot{m}_{choke}$ (%)	0.10	0.05	–
PR_{dc}	2.064	2.076	2.077
Deviation PR_{dc} (%)	0.54	0.07	–
η_{dc}	81.34	82.35	82.50
Deviation of η_{dc} (%)	1.24	0.18	–

3 Results and Discussion

3.1 Grid Dependency Test and Validation

A grid dependency result of NASA Stage 37 (smooth casing case) is shown in Table 1. The results indicated that the deviation of mass flow rate at chocking condition, total pressure ratio, and adiabatic efficiency at design condition are less than 0.2% when the mesh density reaches 0.59–0.91 million nodes. To reduce the computation time as well as increase the accuracy of the results, mesh 2 with 0.59 million nodes was selected for validation and further calculations. In Fig. 3, the numerical model of NASA Stage 37 was validated by comparing with the experiment data [10]. The numerical results presented a good agreement with the experiment data of total pressure ratio and adiabatic efficiency.

3.2 Effect of Multi-Bleed Casing Treatments on Tip Clearance Flow

Figure 4a demonstrates the effects of the Single-Bleed (SB), Double-Bleed (DB), and Triple-Bleed (TB) on the aerodynamic performance of NASA Stage 37, in comparison with the SC case. The results showed that the stall inception was delayed by the operating range enhancement from 0.9385 to 0.9298. In addition, the adiabatic efficiency increased marginally, and the total pressure ratio was slightly reduced. Figure 4b clarifies the operation range extension by comparing the stability and performance of the compressor among four cases: SC, SB, DB, and TB. Additionally, Fig. 4c indicates the gain in adiabatic efficiency are marginal, while the reduction of total pressure ratio is unremarkable in SB, DB, and TB cases. Consequently, the Multi-Bleed in the DB and TB cases improved the stability and aerodynamic performance of the compressor more than the SB.

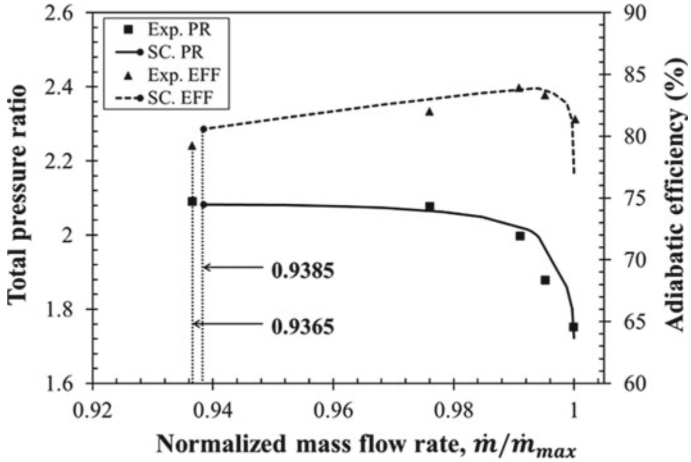

Fig. 3 Numerical validation of NASA Stage 37

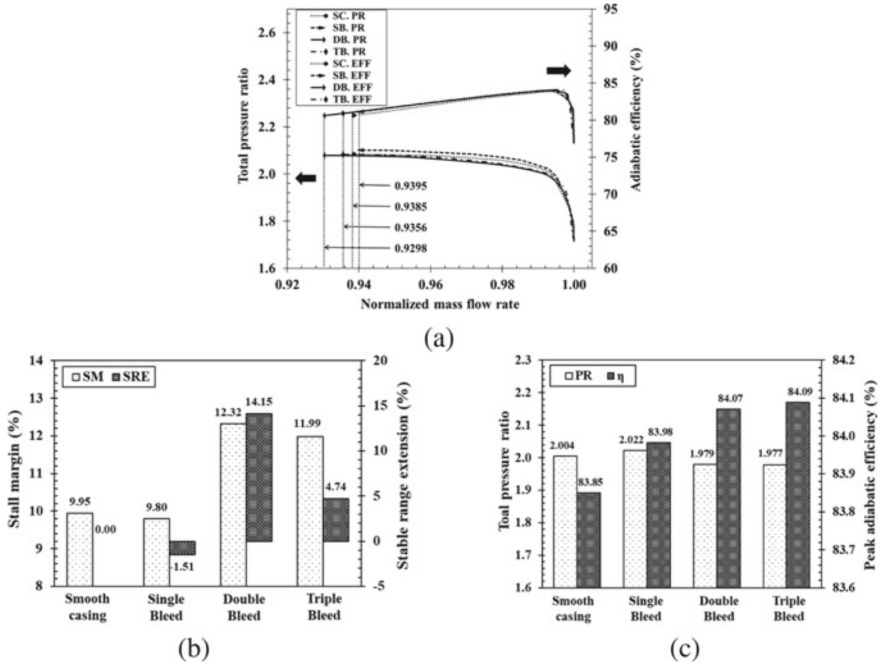

Fig. 4 Influence of multi-bleed casing treatment types on aerodynamic performance in NASA Stage 37: **a** performance curves, **b** SM and SRE, **c** PR and η

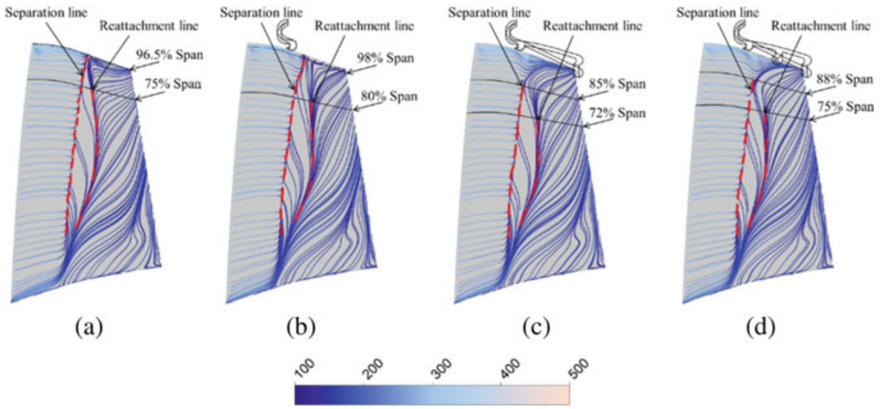

Fig. 5 Streamlines near rotor suction surface at near-stall condition: **a** SC, **b** SB, **c** DB, **d** TB

Figure 5 illustrates the streamlines near the suction surface of the rotor at the near-stall condition for the four cases: SC, SB, DB, and TB. As shown in Fig. 5a, the separation line near the mid-chord is pushed backward by the recirculation flow, which appears in the DB and TB cases as shown in Fig. 5c and d, respectively. Moreover, the length of the separation and reattachment line was reduced significantly by 85% and 72% with the DB case, respectively, 88% and 75% with the TB case, respectively, compared with 85% in the SC case. In contrast, the length of the separation and reattachment line reduced slightly (98% and 80%, respectively) compared with the SC case.

Figure 6 shows the relative Mach number contours at 95% span at the near-stall condition for four cases. The low-speed zones are indicated by regions with a Mach number value under 0.6. The low Mach number regions near mid-pitch and around both the pressure side and suction side of the downstream of the blade reduce considerably with applying the SB, DB and TB (Fig. 6b, c, d) compared to SC (Fig. 6a). In addition, the separation after mid-chord occurs on the suction side of the rotor in the SC and SB cases, while the separation is reduced remarkably in the DB and TB cases.

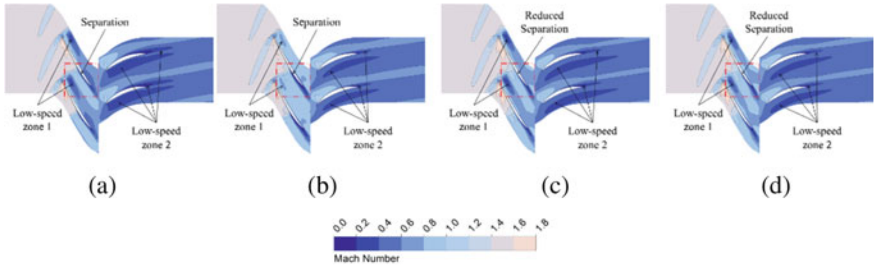

Fig. 6 Relative Mach number on 95% blade span at near-stall condition in NASA Stage 37: **a** SC, **b** SB, **c** DB, **d** TB

4 Conclusion

Aiming to increase the stability of a transonic axial compressor, NASA Stage 37, multi-bleed casing treatments, was numerically investigated using 3D RANS analysis. It was confirmed that the DB and TB cases increased the SM, SRE and efficiency, but slightly decreased the total pressure ratio compared to those of the SC. When compared to SC, the increasement of SM was 2.37% and 2.04%, respectively, and the rise of SRE 14.15% and 4.74%, respectively. With the multi-bleeding channels, the low momentum air would still be reduced significantly from the tip clearance region. Thus, the performance of the compressor was enhanced greatly. Based on this study's results, the geometry of multi-Bleed will be optimized using the multi-objective optimization technique to maximize aerodynamic performances of NASA Stage 37.

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