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# Aerodynamic performance of transonic axial compressor with a casing groove combined with blade tip injection and ejection

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ABSTRACT

Blade tip ejection was introduced to a casing groove combined with tip injection in a transonic axial compressor with NASA Rotor 37. A parametric study of compressor performances was performed using three-dimensional (3-D) Reynolds-averaged Navier–Stokes equations with the $k$–$\epsilon$ turbulence model. Effects of three geometric parameters and one operating parameter, i.e., the front and rear lengths and height of the casing groove, and the mass flow rate of groove ejection, on the performance parameters, i.e., the total pressure ratio, adiabatic efficiency, stall margin, and stable range extension, were investigated in the parametric study. The application of a casing groove combined with tip injection and ejection was found to be effective in the simultaneous improvements of adiabatic efficiency, stall margin, and stable range extension without loss of the total pressure ratio of the transonic axial compressor, compared to the case with a casing groove with injection only, and a smooth casing.



## 1. Introduction

Complex flow phenomena in the tip clearance of an axial compressor strongly affect aerodynamic performances including the pressure rise, efficiency, and stable range extension of the compressor. Special techniques such as casing treatment and tip injection have been used to control the tip clearance flow. Casing treatment using circumferential casing grooves has been proven to extend the compressor stall margin and stable range extension with a small decrease in efficiency. Also, tip injection is known to improve aerodynamic performance by energizing the airflow near the blade tip region.

Many experimental and numerical studies have been carried out to investigate the tip clearance flows of axial compressors. Smith and Cumpsty [1] demonstrated a 23% drop in the maximum pressure rise and a 15% increase in the flow coefficient at the stall condition, with an increase in the tip clearance of up to 6% of the blade chord. Wisler [2] confirmed a 1.5% drop in the peak efficiency when the tip clearance was doubled in a low speed compressor.

There have been many studies of circumferential casing grooves. Rabe and Hah [3] demonstrated that the stall margin and stable range extension increases as the depth of circumferential casing grooves decreases in a single-stage transonic axial compressor. Kim et al. [4,5] carried out a performance evaluation and optimization of circumferential casing grooves on a transonic axial compressor with NASA Rotor 37.

As for the tip injection, Benhegouga and Ce [6] tested the effects of the injection angle of tip injection on the performance of a transonic axial compressor with an injection mass flow rate of 2%. Wang et al. [7] suggested that tip injection increases the stable range and total pressure ratio of a compressor with almost fixed adiabatic efficiency. Tip injection combined with a casing groove has been investigated in order to improve compressor aerodynamic performance parameters including efficiency, stall margin, and stable range extension. Beheshti et al. [8] studied numerically the performance enhancement of a transonic axial compressor using blade tip injection coupled with a casing groove. The stall point predicted by their numerical simulation is 93.60% of the choking mass flow rate with a predicted stall margin of 9.34%. The experimental data reported by Dunham [9] are 92.50% of the choking mass flow rate for the near-stall condition and 13.65% for the stall margin. Khaleghi et al. [10] described the effects of the injection angle of tip injection combined with a casing groove on the stability enhancement of an axial compressor. Kim et al. [11] performed a parametric study of the aerodynamic performance of a transonic axial compressor with a casing groove combined with tip injection using three design parameters: the leading edge length, the trailing edge length, and the height of the casing groove. Kim et al. [12]

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**Nomenclature**

| | | | |
|---|---|---|---|
| $C$ | chord length of blade tip | $P_t$ | total pressure |
| $L_{LE}$ | front groove length | $\eta$ | adiabatic efficiency |
| $L_{TE}$ | rear groove length | $T_t$ | total temperature |
| $D$ | height of groove | SM | stall margin |
| $\dot{m}$ | mass flow rate | SRE | stable range extension |
| RANS | Reynolds-averaged Navier–Stokes | $\gamma$ | specific heat ratio |
| PR | total pressure ratio | | |

performed an aerodynamic optimization of a transonic axial compressor with a casing groove combined with tip injection to find the optimum depth and location of the casing groove in order to maximize the stall margin and peak efficiency of the compressor.

Koff et al. [13], Hobbs [14], and Nolcheff [15] created a recirculation of high pressure flow from the rear to the front on a compressor shroud. This high pressure flow is bleed from the shroud where the pressure is maximum, and is reinserted directly on the shroud to energize the low momentum fluid, and finally to extend the operating range of the compressor without a casing groove. Strazisar et al. [16] suggested an endwall airflow recirculation that bleeds air as a wall jet downstream of a preceding rotor blade row, and injects air on the compressor shroud in front of the blade tip to increase the stall margin and stable range extension. They showed that the stable range extension steadily increases with an increase in tip injection. Hathaway [17] reported an increase in stall range and compressor efficiency by reducing the casing endwall blockage with injection and bleed configuration combined in a single transonic fan rotor (NASA Rotor 67). The advantages of a combination of tip injection and bleeding are removing the low momentum airflow and energizing the airflow in the blade tip region.

Based on the works of Kim et al. [11,12] and Hathaway [17], a configuration that combines tip injection and ejection with a casing groove in a transonic axial compressor, is proposed in the present work in order to enhance the aerodynamic performance and stable range extension of the compressor. An evaluation of the performance of the proposed compressor was made by solving three-dimensional (3-D) Reynolds-averaged Navier–Stokes (RANS) equations. The front and rear lengths and the height of the circumferential casing groove were selected as the geometric parameters, and the ejection mass flow rate was considered as an operating parameter for the parametric study.

## 2. Numerical analysis

### 2.1. Description of geometry

The compressor considered in this investigation is a transonic axial compressor using NASA Rotor 37 at a speed of 17188.7 rpm (1800 rad/s). The additional design specifications are listed in Table 1. The blade airfoil sections of NASA Rotor 37 are designed using multiple circular arcs. From the AGARD report by Dunham [9], the total pressure ratio and polytropic efficiency are 2.106 and 88.90%, respectively, at the designed mass flow rate of 20.19 kg/s (96.50% of the choking mass flow rate) at a reference temperature of 288.15 K and reference pressure of 101,325 Pa.

Fig. 1 shows the reference single casing groove combined with tip injection and ejection in the transonic axial compressor. The casing groove is circumferential and mounted on the blade tip of the rotor, and located near 30% upstream and downstream of blade chord tip. The front and rear groove lengths of the groove are divided at 50% blade chord, as shown in Fig. 1. A constant jet flow is injected into the casing groove from the injection slot located on

**Table 1**
Design specifications of axial compressor [9].

| | |
|---|---|
| Number of rotor blades | 36 |
| Rotational speed (rpm) | 17,188.7 |
| Choking mass flow rate (kg/s) | 20.93 |
| Tip clearance $\tau$ (mm) | 0.356 |
| Chord length of blade tip (mm) | 27.79 |
| Inlet hub-tip ratio | 0.7 |
| Blade aspect ratio | 1.19 |
| Tip relative inlet Mach number | 1.48 |
| Hub relative inlet Mach number | 1.13 |
| Tip solidity | 1.29 |
| Ratio of mass flow rate at near-stall point to that at choking point | 0.925 |

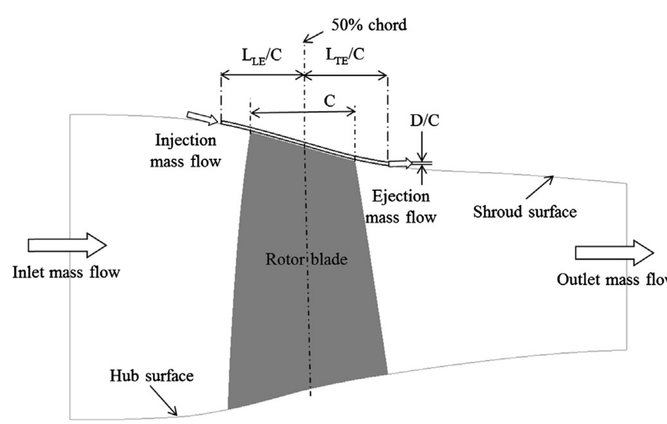


**Fig. 1.** Meridional plane of casing groove combined with blade tip injection and ejection [9].

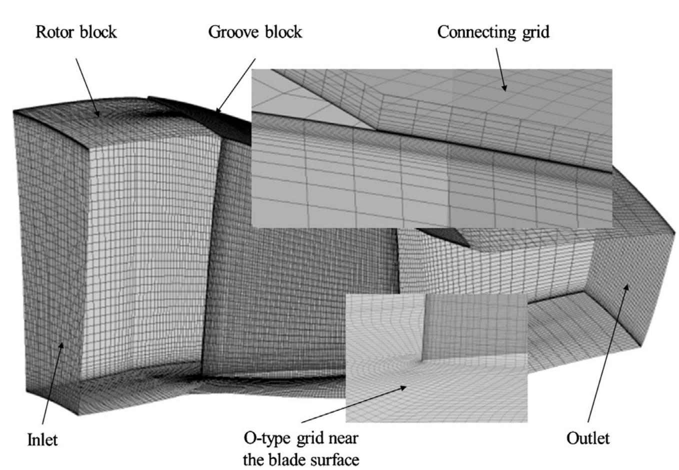


**Fig. 2.** Computational domain and grid system.