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Role of tip injection in desensitizing the compressor to the tip clearance size

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ABSTRACT

Numerical simulations are performed to investigate the role of tip injection in desensitizing a transonic compressor rotor to the detrimental effects of tip leakage flow. First, the effects of tip clearance size on the compressor stability and performance are investigated. Endwall injection of high-speed fluid upstream of the blade is then applied to the compressor with different tip clearance sizes. Results reveal that tip injection can effectively desensitize the compressor stability to the tip clearance size and improve the total pressure ratio, at the expense of some efficiency loss. It is further found that the larger the tip clearance size, the greater the stability enhancement and the smaller the efficiency penalty due to injection. The near-stall endwall flow structures for different tip clearance sizes, with and without injection, are also investigated in the current study. Results suggest that tip clearance size does not influence the compressor stalling mode, whereas endwall injection has the potential to change it (i.e., from “wall-stall” to “blade-stall” with the injection applied in the current study).

1. Introduction

The leakage flow from the tip of the blades is known to have detrimental effects on both the operability and performance of aero-compressors [1]. In transonic compressors, the interaction between the shock and the leakage vortex is known to create large zones of low momentum fluid immediately downstream of the interaction [2–4]. Beheshti et al. [5] investigated the effect of tip clearance size on the stability and performance of a NASA Rotor-37 by conducting steady numerical simulations. Results revealed that a large tip clearance is detrimental to the compressor stability and performance due to the formation of a strong tip leakage vortex. The effect of circumferential groove casing treatment on controlling the tip leakage vortex was further investigated in [5]. Results showed that endwall treatment is more efficient at a large tip clearance due to the better capability of circumferential grooves in controlling the tip leakage vortex. Zhang et al. [6] numerically investigated the effects of different upstream boundary layer thicknesses and tip clearance sizes on the endwall flow of a low-speed compressor rotor. They showed that the increased tip clearance size causes the total pressure ratio and efficiency to reduce for the whole annulus mass flow range. The effect of tip clearance variation has been investigated by Guinet et al. [7]. It was found that casing treatment is more beneficial for an increased tip clearance, as compared to a small one. Tip injection is found to be the most effective approach in providing range extension and is investigated by a large number of researchers (e.g., [8–25]): Weigl et al. [11] studied steady and unsteady injection on a transonic compressor rotor. They found that range extension obtained by tip injection is mostly due to steady injection (i.e., the stability enhancement obtained with unsteady injection was only slightly higher than that achieved by steady injection). Suder et al. [14] studied the effects of injection velocity and circumferential configuration of discrete injectors on the stability of a transonic compressor rotor. The casing mounted injectors which penetrated 5.1 mm from the casing into the flow field were located 200 percent of rotor tip axial chord upstream of the rotor. Stability improvement was investigated at 70 and 100 percent speeds. The maximum range extension achieved at 100 percent speed was found to be significantly lower than that measured at 70 percent. Their results further showed that range extension is related to the total extent of injection but not related to the circumferential arrangement of injection locations. Numerical simulations of tip injection have been conducted by a number of researchers to uncover the physical mechanisms that postpone stall inception and to investigate some of the parameters that affect the injector effectiveness (e.g., [15–21]). Kim et al. [22] and [23] investigated tip injection

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Nomenclature

P_0	total pressure
T_0	total temperature
$y+$	non-dimensional wall distance
η	efficiency

Subscripts

adb	adiabatic
amb	ambient
j	jet

Table 1
NASA Rotor-67 representative values.

Characteristic	Value
Number of blades	22
Design rotational speed (RPM)	16 043
Tip speed (m/s)	429
Inlet tip relative Mach number	1.38
Design mass flow rate (kg/s)	33.25
Design pressure ratio	1.63
Design tip clearance (mm)	1.01
Average aspect ratio	1.56
Tip solidity	1.29
Hub solidity	3.11
Inlet hub/tip radius ratio	0.375
Exit hub/tip radius ratio	0.478

Table 2
Rotor configurations.

Configuration	Tip clearance gap (mm)
A	0 (zero tip clearance)
B	1.01 (nominal tip gap)
C	2.02
D	3.03

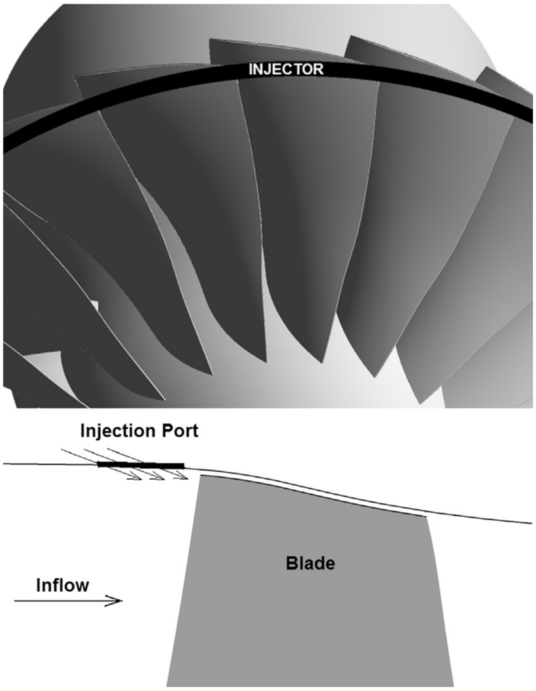

Fig. 1. Injector configuration.

combined with groove casing treatment on a transonic compressor and showed that it is beneficial to both the compressor stall margin and its peak adiabatic efficiency. The effect of tip water injection on the stability of a high speed compressor rotor was studied by Luo et al. [25]. It was found that water injection can be competitive to tip air injection in stability enhancement. Although tip injection has been extensively studied, investigations concerning its role in eliminating the effects of tip clearance size are seldom reported in the open literature.

The main objective of the current study is to understand the impact of endwall injection in desensitizing a high-speed compressor to the detrimental effects of tip clearance flow. The three dimensional CFD code, CFX, has been employed to numerically solve the compressible Navier–Stokes equations around a NASA Rotor-67.

2. Configuration

The test case is a NASA Rotor-67, designed and tested at NASA Lewis Research Center. Table 1 gives the characteristic values for this high-speed rotor [26]. In order to study the effect of tip clearance size on the stability of the test case, four rotor geometries having different tip clearance sizes were generated which are listed in Table 2. Furthermore, an annular casing mounted injector was placed upstream of the blade in each configuration. The injection port is roughly 15.5 mm in width and is designed to inject high speed air with a radial angle equivalent to 20 degrees relative to the casing wall, as shown in Fig. 1. Finally, it should be noted that the center of the injection port is located at roughly 25% tip axial chord upstream of the blade leading-edge.

3. Numerical details

The computational grid, which is generated by using Ansys-TurboGrid and ICEM-CFD, is shown in Fig. 2. It consists of three main domains: inlet, rotor, and outlet. The inlet domain (which includes the injection port) is simulated in the stationary frame of reference. The flow region close to the blade has been discretized using an O-type grid, which includes 153 × 19 nodes (around the blade). For the outer part, however, the H-type mesh has been used. For Configurations A and B, this H-type mesh consists of 187 × 59 × 101 nodes in the streamwise, circumferential and spanwise, respectively. 40 nodes are used in the radial direction to describe the tip clearance gap. The grids generated for Configurations C and D are the same as Configuration B, except in that the number of nodes in the radial direction in the tip region is increased to 56 and 72, respectively. At the injection face in each configuration, 40 nodes are used in the axial direction. The grid clustering is applied near solid surfaces to keep the value of $y+$ less than or equal to 1 (e.g., near the injection port, which is located closed to the blade, $y+$ varied from roughly 0.1 to 0.9 in different cases). The governing equations are the 3-D compressible unsteady Reynolds-averaged Navier–Stokes. The convection terms in the equations have been discretized by using a High-Resolution scheme. The flow field was assumed to be fully turbulent and the turbulence model was chosen to be k–ω shear stress transport. As reported by Huang et al. [27] and [28], SST k–ω can accurately model transverse injection in supersonic flows. The working fluid passing through the rotor was assumed to an ideal gas. For time-accurate calculations, an implicit second-order Euler method was used to discretize the equations in time. Furthermore, the time step was chosen to be 2.833e–6 s and four internal iterations were performed at each time step. The boundary conditions applied for the single blade passage simulations are as follows: At the inlet