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Effect of blade tip winglet on the performance of a highly loaded transonic compressor rotor

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Abstract The tip leakage flow has an important influence on the performance of transonic compressor. Blade tip winglet has been proved to be an effective method to control the tip leakage flow in compressor, while the physical mechanisms of blade tip winglet have been poorly understood. A numerical study for a highly loaded transonic compressor rotor has been conducted to understand the effect of varying the location of blade tip winglet on the performance of the rotor. Two kinds of tip winglet were designed and investigated. The effects of blade tip winglet on the compressor overall performance, stability and tip flow structure were presented and discussed. It is found that the interaction of the tip winglet with the flow in the tip region is different when the winglet is located at suction-side or pressure-side of the blade tip. Results indicate that the suction-side winglet (SW) is ineffective to improve the performance of compressor rotor. In addition, a significant stall range extension equivalent to 33.74% with a very small penalty in efficiency can be obtained by the pressure-side winglet (PW). An attempt has been made to explain the fundamental mechanisms of blade tip winglet in detail.

1. Introduction

The tip leakage flow has a detrimental impact on the efficiency, pressure rise and stability of axial compressors.[1] There are two aspects of the tip leakage flow; one is blockage and the other one is aerodynamic loss.[2–4] Complicated tip flow structures are generated by the tip leakage flow and its interactions with the passage shock wave, the casing boundary layer and the blade wake in transonic compressor rotors, which are often considered as the reasons of rotating instability. The investigation of tip leakage flow in axial transonic compressor rotors has received an increasing interest in the published reference, and some basic understanding has been revealed. Suder and Celestina[5] have shown that the passage shock wave/tip leakage vortex interaction plays a major role in generating endwall blockage of a highly loaded transonic axial compressor rotor. Chima[6] has carried out a numerical study on the interaction of tip leakage vortex, the passage shock wave and the endwall boundary layer. Yamada et al.[7] considered tip leakage vortex breakdown as a possible cause of stall inception in axial transonic compressor rotors.

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A variety of active and passive flow control methods have been studied to control tip leakage flow in axial compressor. Bae[8] investigated the use of three types of fluidic actuators to control the tip clearance flows in a linear cascade. They found that directed synthetic jet and steady directed jet can eliminate tip clearance-related blockage effectively. Suder et al.[9] reported on the application of discrete tip injection to a high-speed axial compressor to enhance compressor stability. They achieved a 6% reduction in stalling flow coefficient when injecting 2% of the annulus flow at design speed. Lu et al.[10] investigated the fundamental mechanisms of axial skewed slot casing treatment and their influences on the subsonic axial flow compressor rotor flow field. Legras et al.[11] studied numerically the influence of circumferential casing grooves on the tip leakage flow and its resulting vortical structures. Hah and Shin[12] investigated the detailed flow behavior in a modern transonic fan with a compound sweep. Compound sweep was found to be an effective means of controlling the tip flow structures.

It has been recognized that the use of special blade tip geometries can be effective in reducing tip leakage flow. Lu et al.[13] conducted a computational study on the function of blade tip cutting in axial flow compressors, concluding that the blade tip cutting technique was rather case dependent and the performance of the cut blade is very sensitive to the shape of blade leading edge. Zhang et al.[14] performed an experimental investigation on the effects of suction side squealer tip on the performance of a low-speed axial compressor. Ma et al.[15] conducted an experimental investigation of grooved tip clearance effects on the flow field of a compressor cascade. Zhong et al.[16] studied the effects of blade tip winglets on the aerodynamic performance of a linear compressor cascade. Results indicate that the use of proper tip winglets in a compressor cascade can positively affect the tip flow field by weakening the tip leakage vortex.

However, the use of blade tip winglets has never been investigated in transonic compressor rotors so far. In this paper, the effect of blade tip winglet on the performance of a highly loaded transonic compressor rotor has been investigated with the help of NUMECA software. The purpose of this investigation aims at advancing the understanding of fundamental mechanisms of blade tip winglet in transonic compressor rotors.

2. Compressor model

2.1. Investigated compressor rotor

The axial compressor rotor, NASA rotor 37, was used in the present numerical investigation. As reported by Yamada[7], stall inception phenomena will occur in the blade tip region for this rotor caused by tip leakage vortex breakdown when the tip leakage vortex interacts with the passage shock wave at near stall condition. The detailed parameters of the rotor are summarized in Table 1. The meridional plane of the axial compressor rotor is shown in Fig. 1.[17] As Fig. 1 shows, total pressure and total temperature were measured at two axial stations located upstream of the rotor blade leading edge (Station 1) and downstream of the rotor blade trailing edge (Station 4) near the hub, respectively.[18]

Table 1 Design parameters of rotor 37.

Parameter	Value
Number of rotor blades	36
Corrected rotation speed (r/min)	17188.70
Corrected mass flow rate (kg/s)	20.19
Total pressure ratio	2.106
Adiabatic efficiency	0.877
Tip speed (m/s)	454.136
Tip clearance size (mm)	0.356
Blade aspect ratio	1.19
Tip solidity	1.288
Inlet hub-tip diameter ratio	0.70

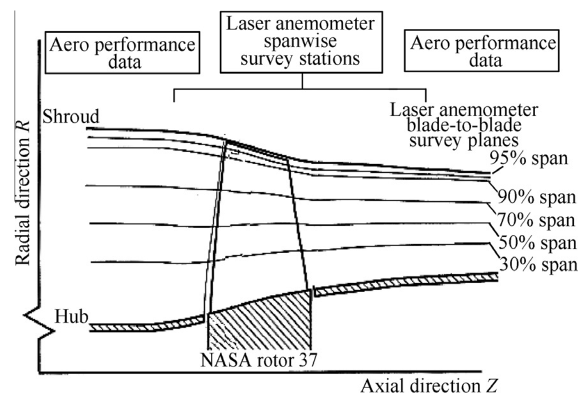

Fig. 1 Locations measured in experiment of rotor 37.[17]

2.2. Blade tip winglet design

Fig. 2 shows the schematics of the different blade tip winglet designs. A blade tip winglet is installed on the suction or pressure side of the blade in the tip region. The blade winglet is arranged along the suction or pressure side tip edge line from the blade leading edge to the blade trailing edge and has a varying width. The blade tip winglet profiles were generated by translating the blade tip profiles away from the corresponding suction and pressure surfaces.[19] The winglet profiles were slightly modified in their leading and trailing regions to maintain a constant leading edge and trailing edge thickness. The contour of the tip winglet/blade junction was smoothed to avoid any discontinuities on the blade surface so that a low increase of the local stresses concentration would be expected.[20] With this rotor tip modification, the tip winglet and rotor blade were designed as one part. The winglet width or extent away from the original blade surface is equal to 2 times of the local blade tip thickness. So the suction-side winglet (SW) case will be referred to as SW2.0 case, while the pressure-side winglet (PW) case will be called PW2.0 case and the baseline tip without winglet case will be called NW case in this paper.

3. Numerical calculation method

3.1. Numerical model

The commercial solver NUMECA/EURANUS was used for the simulation. The flow is modeled using the Favre–Reynolds-averaged N-S equations, which are discretized using a cell-centered