Aerospace Science and Technology 51 (2016) 1–10

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Cantilevered stator hub leakage flow control and loss reduction using non-uniform clearances

Lu Hanan [a], Li Qiushi [a,b,*]

[a] National Key Laboratory on Aero-Engines, Beihang University, Beijing, China
[b] Collaborative Innovation Center of Advanced Aero-Engine, Beihang University, Beijing, China

ARTICLE INFO

Article history:
Received 25 November 2015
Received in revised form 18 January 2016
Accepted 20 January 2016
Available online 22 January 2016

Keywords:
Non-uniform clearance
Hub leakage flow
Cantilevered stator
Aerodynamic performance

ABSTRACT

Hub leakage flow between the cantilevered stator and the hub wall is responsible for the deficit of stator aerodynamic performance, and the interaction between the leakage and main flows leads to leakage vortex and flow blockages in the hub region, thus deteriorating the stator or even the compressor performance. The paper conducts a numerical investigation on the influence of non-uniform clearances on the stator aerodynamic performance in a 1.5-stage axial-flow compressor. The main purpose is to find an aerodynamically preferable clearance shape to control the leakage flow and the associated aerodynamic losses. The clearance shapes considered include uniform, expanding and shrinking clearances from blade leading edge to trailing edge. The computed results show that, compared with the uniform clearance, the expanding clearance has powerful effect on weakening the leakage flow near the leading edge and also has better inhibition of the leakage vortex, thus achieving aerodynamic benefits gain in the hub region. But the shrinking clearance has the opposite effect on the leakage flow and leads to more losses than the uniform clearance. In addition, the overall aerodynamic loss of the stator with the expanding clearance is reduced with the increment of the clearance expansion ratio.

1. Introduction

In modern gas turbine engines, where the compressor section is typically of an axial-flow design, each compressor stage includes a disk with substantial blades mounted on its rim by tenon joints. Although this assembly advantageously permits the blade and disk to be of different materials, it leads to increased weight of the assembly compared with an integrally bladed rotor assembly. The demand for high aerodynamic performance for gas turbine engines, particularly used for military, is requiring the reduction of the weight deficit attributable to the current mechanical joining schemes. It leads to the combinational application of integrally bladed rotors and cantilevered stators. In this assembly, for cantilevered stators, hub leakage flow is found to have a strong impact on compressor overall performance [1,2]. The leakage flow in the hub region can lead to flow blockages by interacting with the main flow near the hub wall. The blockages in axial-flow compressors play an extremely important role in affecting the absolute total pressure rise capability, efficiency, and stable operating range. To improve compressor performance for modern aero-engine use, the leakage flow and the flow blockages should be reduced as much as possible.

In the past decades, many researchers have focused on leakage flow due to the demand for low aerodynamic losses and more favorable designs. Storer and Cumpsty [3] performed both experimental and numerical investigations to study the behavior of tip leakage flow in a linear cascade. The research demonstrated that the overall magnitude of the leakage flow was strongly related to the aerodynamic loading of the blades. Kang and Hirsch [4] conducted experimental investigations in a linear compressor cascade with stationary end-wall at different tip clearance sizes and found that the presence of the tip leakage vortex resulted in the passage vortex moving close to the end-wall and the suction side. Further, Lakshminarayana et al. [5] carried out detailed measurements of the flow field in the tip region of an axial-flow compressor rotor to understand the complex nature of the tip clearance flow. Zhang et al. [6] used stereoscopic particle image velocimetry in a large-scale low-speed axial-flow compressor test facility to analyze the variations of the tip leakage vortex characteristics. Moreover, Sakulkaew et al. [7] performed numerical investigations to explore the effect of different sizes of the rotor tip clearance on compressor efficiency.

All these works are aimed at exploring the loss mechanism associated with the leakage flow for the purpose of reducing the

* Corresponding author at: National Key Laboratory on Aero-Engines, Beihang University, Beijing, China.
E-mail address: liqs@buaa.edu.cn (L. Qiushi).

http://dx.doi.org/10.1016/j.ast.2016.01.013
1270-9638/

Nomenclature

C_p	specific heat capacity	J/(kg·K)
m	mass flow rate	kg/s
Ma	Mach number	
P^*	stagnation pressure	Pa
P	static pressure	Pa
s	specific entropy	J/K
$\dot{S}$	entropy creation rate	J·kg/(K·s)
T	static temperature	K
T^*	stagnation pressure	K
V	flow velocity	m/s
y^+	non-dimensional wall distance	
Δ	increment	

Greek symbols

γ	specific heat ratio

Subscripts

c	clearance flow
in	inlet
m	mainstream flow
out	outlet
ref	reference

Abbreviations

HLV	hub leakage vortex
LE	leading edge
PS	pressure surface
S1	Stator 1
SS	suction surface
TE	trailing edge

corresponding aerodynamic losses and improving the compressor performance. Since the interaction between the leakage and main flows plays a very significant role in the total losses of the compressor, efficiently controlling the strength of the leakage flow may be an effective way to improve the compressor efficiency. However, a simple way to control the leakage flow is to employ different clearance sizes along the chordwise direction, like the simple non-uniform clearance shapes.

The effect of non-uniform clearance shapes on the leakage flow has been investigated in turbine rotors. The research conducted by Gao et al. [8] reported that the front-step and shrinking clearances could reduce the total losses in turbines due to efficiently utilizing the interaction of tip leakage flow with passage secondary flows. Krishnababu et al. [9] found that the cavity tip was advantageous both from the aerodynamic and from the heat transfer perspectives by providing a decrease in the amount of leakage, and hence losses. Moreover, the use of squealer tip for reducing the leakage mass flow and losses has been reported by Prakash et al. [10] and Mischo et al. [11].

For compressors, Mohan and Guruprasad [12] conducted an experimental investigation and found that an axially non-uniform clearance (a smaller clearance from leading edge to mid-chord and a larger clearance from mid-chord to tailing edge) could provide improved performance of a compressor stage. Ma and Li [13] also reported that optimal axially non-uniform tip clearances could improve compressor performance due to weakening the tip leakage vortex and blowing down low-momentum fluids in boundary layers.

The majority of the research, experimental or computational, has focused on the rotor tip leakage flow, and less attention has been given to investigating the cantilevered stator hub leakage flow. However, fundamental differences exist between flows in rotor blade and cantilevered stator rows despite the observed similarities [14]. For turbine rotors, the casing movement relative to the rotors is opposite to the hub movement relative to the cantilevered stator. For compressor rotors, the centrifugal force imposed on the fluids due to the rotor rotation does not exist for fluid in a cantilevered stator passage. These differences lead to significantly different flow structures for the rotor passage and the cantilevered stator passage, and the aerodynamic benefits due to applying non-uniform clearances to rotors may not be directly shifted to the cantilevered stators. Therefore, it is essential to specifically investigate the effect of non-uniform clearances on the cantilevered stator performance.

However, in open literature, only Wang et al. [15] carried out a numerical study to investigate the influence of different clearance shapes on the aerodynamic performance of a stator under the conditions of both stationary and rotating hubs. The results showed that the hub leakage vortex was generated earlier for the stationary hub cases than for the rotating ones. In the scope of the open literature reporting the cantilevered stators, there are still few reports of the application of the non-uniform clearances. Aerodynamic benefits have been achieved when the non-uniform clearances are applied to compressor or turbine rotors. The positive effects of the non-uniform clearances on rotors still motivate researchers to explore the potential aerodynamic benefits gain in the cantilevered stators.

In the real manufacturing process, the assembly error of the cantilevered stator hub clearance has a significant influence on the stator hub leakage loss and further the overall aerodynamic performance. But non-uniform clearance shapes seem to be inevitable due to the assembly error. Therefore, numerical investigations are conducted in this work to study the influence of non-uniform clearances to explore the potential aerodynamic benefits and facilitate advanced cantilevered stator design. This work is to address the following research questions:

(1) How is the concept of non-uniform clearance shapes proposed to be applied to control the cantilevered stator hub leakage flow?
(2) What are the effects of non-uniform clearances on the strength of leakage mass flow?
(3) Could the non-uniform clearance be effective on reducing the stator aerodynamic losses?

Based on the research questions posed, the paper is organized as follows. The first part presents why the concept of non-uniform clearance shapes is introduced to cantilevered stators. For the second part, the effect of non-uniform clearance shapes on the hub leakage flow is studied. The motivation is to try to employ non-uniform clearances to control the strength of the leakage flow. The last part focuses on the influence of non-uniform clearances on the stator performance. The main purpose is to explore the potential aerodynamic benefits gain.

2. Compressor stator used for study

2.1. Cantilevered stator

Similar to cantilevered compressor rotors attached to the hub, stator vanes can be attached at the casing, thus being cantilevered. A schematic description of the cantilevered stator configuration is