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Casing grooves to improve aerodynamic performance of a HP turbine blade

Levent Ali Kavurmacioglu [a,*], Cem Berk Senel [a], Hidir Maral [a], Cengiz Camci [b]

[a] Department of Mechanical Engineering, Istanbul Technical University, Istanbul 34437, Turkey
[b] Department of Aerospace Engineering, The Pennsylvania State University, 223 Hammond Building, University Park, PA 16802, USA

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ABSTRACT

Highly three-dimensional and complex flow structure in the tip gap between a blade tip and the casing leads to significant inefficiency in the aerodynamic performance of a turbine. The interaction between the tip leakage vortex and the main passage flow is a substantial source of aerodynamic loss. The present research deals with the effect of groove type casing treatment on the aerodynamic performance of a linear turbine cascade. Grooved casings are widely used in compressors in order to improve the stall margin whereas limited studies are available on turbines. In this study, various circumferential grooves are investigated using the computational approach for a single stage axial turbine blade. The specific HP turbine airfoil under numerical investigation is identical to the rotor tip profile of the Axial Flow Turbine Research Facility (AFTRF) of the Pennsylvania State University. The carefully measured aerodynamic flow quantities in the AFTRF are used for initial computational quality assessment purposes. Numerical calculations are obtained by solving the three-dimensional, incompressible, steady and turbulent form of the Reynolds-Averaged Navier–Stokes (RANS) equations. A two-equation turbulence model, Shear Stress Transport (SST) k-ω is used in the present set of calculations. Current results indicate that groove type casing treatment can be used effectively in axial turbines in order to improve the aerodynamic performance. Detailed flow visualizations within the passage and numerical calculations reveal that a measurable improvement in the aerodynamic performance is possible using the specific circumferential grooves presented in this paper.

1. Introduction

A gap is required between the rotating blades and the casing in order to allow the relative motion of the blade and to prevent the blade tip surface from rubbing in most turbomachinery systems. The overall aero-thermal performance in a turbomachinery system is strongly related to the leakage flow within the tip gap. The pressure difference between the pressure side and suction side of the blade results in the tip leakage flow that is three-dimensional and highly complex. Approximately one-third of the aerodynamic losses in a rotor row is due to the leakage vortex [1]. When the leaking fluid leaves from the tip gap, it rolls up into a distinct leakage vortex and interacts with the main passage flow including the secondary flows. For this reason, highly complex flow structures appear near the blade tip and lead to inefficiency in terms of aerodynamic performance. The leakage flow also does not contribute to work generation since the flow is not turned as the passage flow [1–4]. In addition to aerodynamic aspect, the leakage flow causes higher thermal loads on the blade tip platform [4,5].

There are many studies in the literature in order to clarify the physics of the tip leakage flow and to reduce its adverse effects on the aero-thermal performance of the turbomachines. Passive control methods applied to the blade tip such as cavity squealer, partial squealer, winglet and carved designs are widely investigated in order to minimize the effects of the leakage flow and secondary flows. Heyes et al. [3] experimentally investigated the aerodynamic performance of partial squealer tips in a linear turbine cascade and obtained that suction side squealer tip geometries were effective in order to reduce the aerodynamic loss. Ameri et al. [6] performed a numerical study on the effect of a cavity squealer tip design on fluid flow and heat transfer. It was noticed that cavity squealer tip reduced the leakage flow rate whereas an increase in the total heat transfer coefficient was observed compared to the flat tip. An experimental study by Azad et al. [4] on 6 different squealer tips in a linear turbine cascade revealed that suction side squealer offered

* Corresponding author.
E-mail addresses: kavurmacio@itu.edu.tr (L.A. Kavurmacioglu), senelce@itu.edu.tr (C.B. Senel), maral@itu.edu.tr (H. Maral), cxc11@psu.edu (C. Camci).

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Nomenclature

Latin symbols

A	rotor passage inlet area
b	groove width
C	true chord
C_a	axial chord
C_p	pressure coefficient
C_{p0}	total pressure coefficient
D_h	hydraulic diameter (4*A/P)
g	groove depth
h	blade span
k	turbulent kinetic energy
$\dot{m}_i$	inlet mass flow rate
$\dot{m}_l$	leakage mass flow rate
M	Mach number
N	number of grooves
p	pressure
P	rotor passage inlet perimeter
p_0	total pressure
U	velocity
U_m	reference velocity
x	axial direction
y^+	dimensionless wall distance
ΔC_{p0}	total pressure loss coefficient

Greek symbols

α	flow angle
μ	dynamic viscosity
τ	tip gap height
τ/h	tip clearance
ω	specific dissipation

Abbreviations

AFTRF	Axial Flow Turbine Res. Facility
CFD	Computational Fluid Dynamics
CG	Casing Groove
LE	Leading Edge
LV	Leakage Vortex
PS	Pressure Side
RANS	Reynolds Averaged Navier Stokes
TPV	Tip Passage Vortex
TE	Trailing Edge
SS	Suction Side

better aero-thermal performance compared to cavity and pressure side squealer. Camci et al. [7] experimentally studied the aerodynamic characteristics of partial squealer rims in a single-stage, large-scale, low-speed, rotating axial flow turbine research facility (AFTRF) of the Pennsylvania State University. They found a better aerodynamic performance in the case of suction side squealer instead of cavity squealer. Key and Arts [5] compared the leakage flow characteristics of the flat and the cavity squealer tip geometries in a linear turbine cascade at low & high-speed conditions. It was measured that squealer tip designs provided lower aerodynamic loss with respect to the flat tip under specified conditions. Newton et al. [8] measured pressure coefficient and heat transfer coefficient in the tip gap for flat, suction side and cavity squealer tips in a linear cascade and supported their results with numerical computations. Their results showed that suction side and cavity squealer reduced the heat transfer to the blade tip. Kavurmacioglu et al. [9] performed detailed numerical aerodynamic calculations for a partial squealer tip and obtained a decrease in aerodynamic loss compared to flat tip. A numerical investigation on different tip geometries by Krishnababu et al. [2] indicated that cavity squealer reduced the aerodynamic loss and the heat transfer to the blade tip. Lee and Kim [10] experimentally investigated the flow structure over a cavity squealer tip design in a linear cascade turbine. Their results indicated that cavity squealer was better than flat tip in reducing the leakage flow rate. Zhou and Hodson [11] used experimental and numerical methods to study the aero-thermal performance of the cavity squealer tips and investigated the effects of the squealer width and height. Liu et al. [12] conducted a numerical investigation on the flow and the heat transfer for pressure side, suction side and cavity squealer tip geometries. The calculations revealed that cavity squealer had minimum aerodynamic loss while pressure side squealer provided minimum heat transfer to the blade tip. Schabowski and Hodson [13] found lower aerodynamic loss in the case of cavity squealer compared to the suction side squealer by their numerical and experimental studies. Ma and Wang [14] studied the aerodynamic effects of various tip designs including pressure side, suction side and cavity squealer tip geometries in a low-speed turbine cascade. Experiments showed that cavity squealer tip provided lower aerodynamic loss. Maral et al. [15] carried out a numerical investigation on the aero-thermal effects of squealer width and height of cavity squealer tips with a parametric approach.

Apart from the conventional turbine tip design approaches; there is also a passive control method, which is widely used in axial compressors in order to improve the stall margin of the turbomachine [16–20]. Studies indicate that the use of grooves that is defined as casing treatment increases the stable working condition of the compressors considerably. Grooves can be formed in different ways. Circumferential grooves correspond to the one of the most common designs. However, few studies are available on the axial turbines in the literature. To author's knowledge, the experimental study reported by Gumusel [21] is one of the limited studies that investigates the effects of casing treatment in axial flow turbines. In this study, the effect of casing treatment on over tip leakage flow was investigated in the (AFTRF). They found that the curved casing treatment in axial direction reduced the leakage flow rate and the momentum deficit in the core of the leakage vortex. Gao et al. [22] carried out a numerical investigation on the effect of a counter-rotating rotor casing to reduce the total aerodynamic losses in un-shrouded turbines using the interaction between the tip leakage vortex and the passage vortex. They concluded that the casing contouring could be used efficiently in turbines to reduce the total aerodynamic loss despite an increase in local losses.

The present research deals with the aerodynamic effects of circumferentially grooved casing treatments for a high-pressure axial turbine rotor. Different types of circumferential grooves are investigated in order to understand the flow physics in a linear cascade arrangement. Current results show that groove type casing treatment can be used effectively in axial turbines in order to improve the aerodynamic performance. Numerical calculations and numerical flow visualizations within the passage reveal that improvements in the aerodynamic performance of a turbine can be achieved using circumferential grooves.

2. Numerical method

2.1. Definition

The axial turbine blade profile and turbine operating conditions used for the computations belong to the Axial Flow Turbine Re-