International Journal of Heat and Fluid Flow 000 (2016) 1–9

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijheatfluidflow

Numerical investigation of secondary flows in a high-lift low pressure turbine

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ARTICLE INFO

Article history:
Available online xxx

Keywords:
Low pressure turbine
Endwall flow
Loss mechanism
CFD

ABSTRACT

In turbomachines, secondary flows (or endwall flows) typically originate at the junction between endwalls and the blade surface. Within the blade passage, the strength of the secondary flows is amplified by the crossflow from the pressure to the suction surface of the blade. The enhanced mixing due to secondary flows induce additional losses into the system. This decreases the overall work output and also changes the flow incidence onto the downstream blade rows. Using a series of high-fidelity eddy resolving simulations, the current study attempts to provide an improved understanding for the complex flow physics over the endwalls of a high-lift Low Pressure Turbine (LPT) blade. The effect of three different inflow conditions has been studied. These include a laminar boundary layer (LBL), a turbulent boundary layer (TBL) and wakes with secondary flow (W&S) from an upstream blade row. For the simulations with TBL and W&S, precursor eddy resolving simulations were used to prescribe realistic inflows. The loss generation mechanisms were subsequently studied both at the endwall and the midspan, which includes evaluating the mass-averaged total pressure loss coefficient (Y_p) and the loss generation rate.

When compared to LBL, additional disturbances from an incoming TBL and wakes with secondary flows enhanced the mixing within the blade passage resulting in a substantial increase in the total pressure loss. Prior to flow transition, incoming wakes with secondary flows increased the local loss generation rate at both the endwall and the midspan in the front portion of the blade passage ($x/C_x < 0.84$). In contrast, in the aft portion of the passage ($x/C_x > 0.8$), the incoming wakes effectively suppressed the separation bubble at the midspan thereby decreasing the local loss generation rate. It is also demonstrated that the wakes shed from the trailing edge at the mid-span mix out rapidly when compared to the passage vortex at the endwall.

1. Introduction

The efficiency of a low pressure turbine (LPT) strongly influences the overall performance of a modern gas turbine aero-engine. The LPT also contributes to about 30% of the total weight of the engine (Opoka, 2007). High-lift blade designs are used in the modern aero engines. Such designs can extract the same amount of work output with a lower blade count thereby reducing the weight of the engine. However, high-lift blades increase a) the risk of boundary layer separation on the suction surface and b) the strength of secondary flows. There are several studies addressing the issue of the midspan separation and its control (Hodson and Howell, 2000, 2005; Opoka and Hodson, 2008). The current authors (Cui et al., 2016) have also reported the effect of different external disturbances on the separated shear layer transition at the midspan.

Secondary flows typically generate around 30% of the overall loss in a blade row. Most of the previous investigations of secondary flows have either been experimental or low-fidelity numerical studies (using Reynolds Averaged Navier–Stokes - RANS). The objectives of these studies can be broadly classified into understanding the: a) endwall flow features, b) loss generation mechanisms and c) effect of inflow conditions. A brief review of the relevant literature is given below:

Flow features at endwall: Early studies on secondary flows focused on understanding the overall flow features Langston (2001). Fig. 1 shows the widely accepted topology of the endwall flow. The incoming boundary layer separates under adverse pressure gradient, which forms the suction and pressure legs of the horseshoe vortex. Subsequently, the pressure leg merges with the suction leg to form the passage vortex. However, disagreement still exists regarding the details of the secondary flow structure. One of them is the development of the suction leg of the horseshoe vortex.

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2016.05.018
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Nomenclature

δ^*	Boundary layer displacement thickness
θ	Boundary layer momentum thickness
C_x	Axial chord
C_p	Pressure coefficient $(P_{0in} - P)/(P_{0in} - P_{TE})$
h	Span
H	Shape factor
TKE	Turbulent kinetic energy
P	Local pressure
P_0	Stagnation (total) pressure
P_y	Pitch
Q	Q-criterion
Re	Reynolds number based on U_{TE} and C
U	Velocity
Y_p	Total pressure loss coefficient $(P_{0in} - P_0)/(P_{0in} - P_{TE})$

Subscripts

in or 1	Inlet
TE or 2	Trailing edge or exit

Others

$\bar{X}$	Area averaged quantity
$\tilde{X}'$	Mass averaged quantity

Sharma and Butler (1987) and Wang et al. (1997) demonstrated that this leg wrapped around the passage vortex, eventually merging with the passage vortex. On the other hand, Goldstein and Spores (1988) argued that the suction side leg of horseshoe vortex always travelled above the passage vortex. The origin of the counter vortex downstream of the trailing edge is also an open question. Hodson and Dominy (1987) proposed that the relative skew of the boundary layer over the blade results in a counter vortex, while Wang et al. (1997) showed that the counter vortex is induced by the strong passage vortex.

Loss generation mechanisms: Secondary kinetic energy is often used to quantify the total endwall loss. However, the lack of correlation between secondary kinetic energy and total loss is reported by Denton and Pullan (2012). Ingram et al. (2005) also demonstrated that a blade designed with a reduced level of secondary kinetic energy can still increase loss. The relation between loss generation rate and Reynolds stresses has been experimentally investigated by MacIsaac et al. (2012). The importance of shear stress in the loss generation downstream of the trailing edge was also demonstrated by these workers. Due to the limitation of accessibility within the blade passage, only measurements downstream of the trailing edge were reported in MacIsaac et al. (2012).

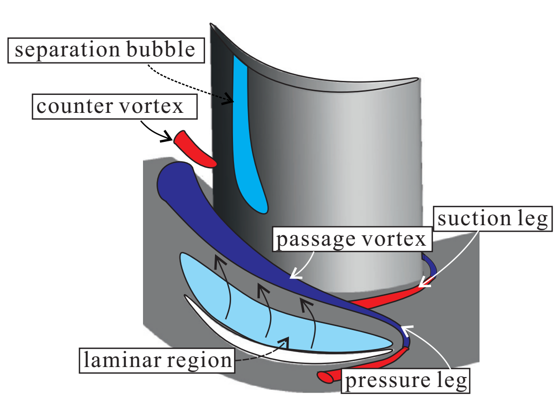

Fig. 1. Sketch of typical endwall flow structures in low pressure turbines.

Table 1
Specification of T106A cascade.

Reynolds number (Re)	1.6×10^5
Chord (C)	198 mm
Axial chord (C_x)	170 mm
Pitch	158 mm
Span (h)	375 mm
Inlet angle (α_1)	−39.7°
Design exit flow angle (α_2)	63.2°
Flow coefficient (Φ)	0.83
Inlet velocity (U_{in})	≈ 6.8 m/s
Outlet velocity (U_{TE})	≈ 12˜m/s

Effect of inflow conditions: de la Blanco et al. (2003) reported that the state of the incoming endwall boundary layer plays an important role in endwall loss generation. By simulating the wakes using upstream moving bars, Steurer et al. (2014) studied the effects of incoming wakes on the secondary flow. The effect of secondary flow from the upstream blade row was not considered in this study.

The investigations summarized above have provided valuable insights into the physics of secondary flows. However, the knowledge of flow physics and loss generation mechanisms concerning endwall flows is still limited; either due to the restricted access to the endwall zones in measurements (and general flow complexity) or due to the assumptions involved in the low-fidelity models. This lack of understanding impedes the development of more accurate secondary loss prediction models and the flow control methods for loss reduction. Using a series of high-fidelity eddy resolving simulations, the current study attempts to provide an improved understanding of the endwall flows and the associated loss generation mechanisms in high-lift low pressure turbines. The effect of three different inflow conditions have been studied. These include a laminar boundary layer (LBL), a turbulent boundary layer (TBL) and wakes with secondary flow (W&S) from an upstream blade row.

This paper is organized as follows. Section 2 briefly describes the numerical methodology and computational domain used in the current study. Section 3 presents a detailed investigation of the endwall flow features and loss mechanisms both with and without the influence of different inflow conditions. Section 4 concludes the study.

2. Computational methodology

The endwall of a T106A cascade has been considered in the current study. The T106A cascade has been widely used in the research community in the context of studying transitional flow over the suction surface at midspans. Table 1 gives the key design parameters of the T106A cascade. Fig. 2(a) shows the computational domain and boundary conditions in the $x - y$ plane. This domain was extruded in z direction to resolve half a blade span (50%˜h). No-slip and inviscid wall boundary conditions were imposed on the bottom and top boundaries, respectively. The latter assumption and its implications are described further later.

2.1. Inflow boundary conditions

In total, three simulations with different inflow conditions have been carried out. An overview of the test cases is given in Table 2. The mean velocity profiles at the inlet were specified based on the measurements of Blanco (2004). Fig. 3 shows the incoming mean velocity and the associated turbulent kinetic energy profiles imposed at the inlet for the LBL and TBL test cases, respectively. For the TBL test case, a precursor direct numerical simulation was carried out using the Lund's recycling technique (Lund et al., 1998)

Please cite this article as: J. Cui et al., Numerical investigation of secondary flows in a high-lift low pressure turbine, International Journal of Heat and Fluid Flow (2016), http://dx.doi.org/10.1016/j.ijheatfluidflow.2016.05.018