Aerospace Science and Technology 63 (2017) 33–40

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Numerical investigation of a HPT with different rotor tip configurations in terms of pressure ratio and efficiency

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ARTICLE INFO

Article history:
Received 2 March 2016
Received in revised form 19 November 2016
Accepted 6 December 2016
Available online 15 December 2016

Keywords:
Gas turbine
High pressure turbine
Tip clearance
Tip desensitization
CFD

ABSTRACT

The choice of the most appropriate rotor tip configuration is important, because it helps to avoid high blade tip losses due to the leakage flow that are responsible for efficiency and pressure ratio drops, mainly in High Pressure Turbine (HPT). This subject has been investigated to improve the axial turbines performance. The HPT used in this work is the turbine designed during the Energy Efficient Engine Program (E3 Program). This HPT was evaluated with different rotor tip geometry configurations: without tip clearance (hypothetical condition), with standard tip clearance geometry (flat-tip), with squealer, with winglet and squealer with winglet. Results were obtained based on the three-dimensional turbulent flow calculations making the use of a commercial CFD RANS equation-based solver with the addition of a two-equation turbulence model, in which the numerical solutions were compared with data available in the open literature for a HPT design-point operation. It was determined that for the HPT studied in this work, the machine efficiency can be improved using the rotor tip geometry equipped with winglet tip configuration. However, the rotor tip geometry equipped with squealer–winglet tip configuration presented a better pressure ratio compromise.

1. Introduction

The flow inside turbomachines is unsteady and three-dimensional. As a result of local pressure differences between the pressure and suction sides of the blades an undesirable leakage flow occurs through the rotor tip gap.

Evidently, this leakage flow interacts with the main flow, thereby generating losses. Silva et al. [1] mentioned that, although the gap is small, the tip leakage flow has large effect on the aerodynamics and performance of an axial turbine and its effects are strong in HPT. During the design procedure, it is necessary to evaluate the blade mechanical characteristics to prevent rubbing between rotor blades and its casing [2,3].

The gap value changes considerably during engine operation due to the high thermal loads, aero-mechanical response as well as effects of centrifugal and gas bending stresses. The thermal growth of the disk and blade has a direct effect on the tip gap variations during an aircraft flight envelope [4].

Fig. 1 shows a qualitative tip clearance variation during a standard aircraft flight envelope.

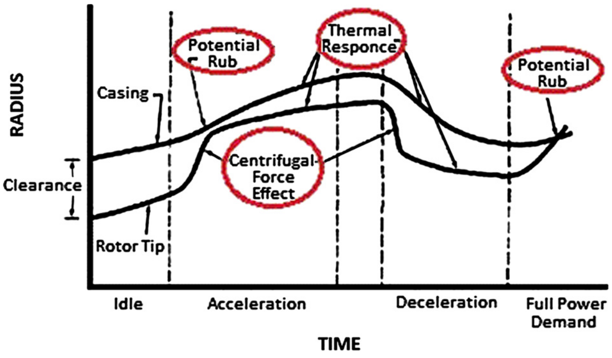

Fig. 1. Variation of tip clearance during a flight envelope [4].

Tallman and Lakshminarayana [5] described that the tip leakage flow and its vortex generation affect the turbine performance due to the production of aerodynamic and thermal losses, increasing the entropy inside the rotor domain, thus disturbing the main flow. Fig. 2 illustrates qualitatively the flow streamlines in a common rotor flat tip configuration.

I – The streamlines, with black color, pass through the gap close to the blade tip surface, increasing the secondary flow losses. It is scraped below the leakage vortex.

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http://dx.doi.org/10.1016/j.ast.2016.12.009

Nomenclature

CFD	computational fluid dynamics
E^3	energy efficient engine
HPT	High pressure turbine
NGV	Nozzle guide vane
P_{in}	inlet static pressure
Pt_{in}	inlet total pressure
P_{tout}	outlet total pressure
RANS	Reynolds average Navier–Stokes
SST	shear stress turbulence
T_{in}	inlet static temperature
U_t	blade tip speed
T_{tout}	total temperature
P_{ref}	reference pressure or atmospheric pressure
$\dot{m}$	mass flow
η	isentropic efficiency

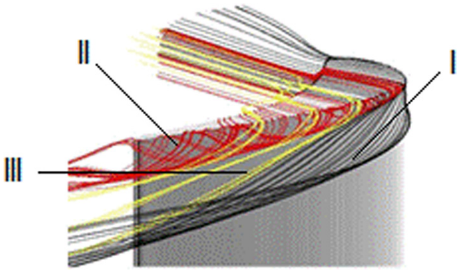

Fig. 2. Schematic drawing showing the leakage flow in a flat tip blade [5]. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

II – The streamlines, with red color, pass through the gap within 10% of clearance height, close to the rotor tip surface.

III – The streamlines, with yellow color, pass through the gap, in the mid passage between rotor tip and casing surfaces, in which this region has a lower wall influence compared with the black and red-colored streamlines. This flow does not roll into the leakage vortex.

According to Schabowski et al. [6], in an unshrouded turbine, the tip clearance is usually of the order of 1 to 2% of the blade span. Booth et al. [7] mentioned that, typically a clearance of 1% of blade span causes 1 to 2% of primary flow to leak and hence, a loss of 1 to 3% on stage efficiency. In the case of high performance axial turbines in order to decrease the tip clearance loss, the rotor tip geometry should be modified to decrease the leakage effects.

Decades of research have been conducted to study and develop new aerothermodynamic characteristics of rotor blade tip geometry solutions to improve the turbine pressure ratio and/or efficiency. Saha et al. [8] define tip desensitization as a method that consists of changing the flow characteristics to reduce the tip leakage flow and heat transfer coefficient on the gap region.

The purpose of this work is to assess the influence of different rotor tip configurations (tip desensitization) on the pressure ratio, efficiency and the flow characteristics inside of a high pressure turbine (HPT) using CFD techniques based on RANS (Reynolds Average Navier–Stokes) simulations. This HPT was developed during the Energy Efficient Engine Program (E^3) as reported by Thulin et al. [9]. Experimental data are available only for flat tip rotor blade configuration. The numerical simulations were performed for baseline rotor (without tip-clearance), flat-tip, squealer, winglet and squealer–winglet.

2. Geometry and its design parameters

The HPT is a single stage turbomachine with uncooled blades. It consists of 24 Nozzle Guide Vanes (NGV) and 54 rotor blades, in each respective row, as shown in Fig. 3. In the test facility, the working fluid is dry air and the main design parameters are:

- Mass-flow ($\dot{m}$): 15 kg/s;
- Blade tip speed (U_t): 390 m/s;

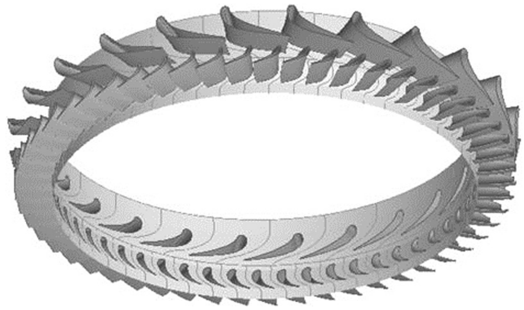

Fig. 3. Three-dimensional geometry of HPT.

Fig. 4. Rotor tip sketches for different configurations.

- Inlet total pressure (Pt_{in}): 607.8 kPa;
- Inlet static temperature (T_{in}): 697 K;
- Total-to-total pressure ratio ($Pt_{\text{in}}/Pt_{\text{out}}$): 4.0;
- Isentropic efficiency (η): 87.7%;
- Aspect ratio (h/c): NGV $=$ 0.53 and Rotor $=$ 0.95;
- Chord (c): NGV $=$ 94.8 mm and Rotor $=$ 43 mm;
- Blade Span (h): NGV $=$ 50.3 mm and Rotor $=$ 42.6 mm.

3. The desensitization study process

3.1. Rotor tip geometry modifications

There is no sufficient and detailed information in the open literature about the best practices to determine the blade airfoil geometry based on tip desensitization methods to minimize the turbine tip losses. However, in this work the geometric modifications were performed following the recommendations described in reference [8], in which some dimensional characteristics are thickness, cavity and width as a function of gap size. In this work, five different geometries characteristics such as: thickness, cavity depth and width, were assessed as a function of gap size as shown in Fig. 4. For all cases, the gap size was considered as 1.5% of the blade height following the reference [10].

The geometrical modifications at the turbine rotor tip for the squealer and winglet shape were made based on the work of reference [8], since this reference also treat the tip desensitization technique in a HPT with a pressure ratio of 1.73. In the present work, all percentages are based on rotor blade height, in which the winglet configuration has a width of 2.7% and a winglet thickness of 2.9% and the squealer configuration has a cavity of 2.35% and a squealer thickness of 0.9%, as shown in Fig. 5. The HPT studied in this work has a total-to-total pressure ratio equal to 4.0 ($Pt_{\text{in}}/Pt_{\text{out}}$).