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# Tip-leakage flow loss reduction in a two-stage turbine using axisymmetric-casing contouring

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**Abstract** In order to reduce the losses caused by tip-leakage flow, axisymmetric contouring is applied to the casing of a two-stage unshrouded high pressure turbine (HPT) of aero-engine in this paper. This investigation focuses on the effects of contoured axisymmetric-casing on the blade tip-leakage flow. While the size of tip clearance remains the same as the original design, the rotor casing and the blade tip are obtained with the same contoured arc shape. Numerical calculation results show that a promotion of 0.14% to the overall efficiency is achieved. Detailed analysis indicates that it reduces the entropy generation rate caused by the complex vortex structure in the rotor tip region, especially in the tip-leakage vortex. The low velocity region in the leading edge (LE) part of the tip gap is enlarged and the pressure side/tip junction separation bubble extends much further away from the leading edge in the clearance. So the blocking effect of pressure side/tip junction separation bubble on clearance flow prevents more flow on the tip pressure side from leaking to the suction side, which results in weaker leakage vortex and less associated losses.

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## 1. Introduction

In the design art of modern gas turbine engine, highly loaded airfoils are more and more widely employed as they result in lower cost and engine weight by reducing the number of blades required at each stage. However, increasing the loading could lead to further challenge to aerodynamic performance and one of them is the tip-leakage flow losses in casing region associated with rotor blade, especially unshrouded turbine blade. The tip-leakage flow contributes negatively to the turbine performance. Previous research has pointed out that tip-leakage flow is one of the dominant loss sources and Denton[1] indicates that it accounts for approximately 1/3 of the total aerodynamic loss.

Because of its detrimental impact on the efficiency and heat transfer, the nature of a tip-leakage flow/vortex has been investigated by many researchers using both experimental and numeral approaches. In their investigations (Moore and Tilton,[2] Bindon,[3] You et al.[4]), much understanding about the detailed flow structure in tip-leakage flow/vortex has been gained. Denton[1] has done a review on the loss mechanism of

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**Table 1** Design parameters of the two-stage high pressure turbine.

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Design rotating speed (r/min) | 12630 | Inlet total pressure (kPa) | 1258.4 |
| Design mass flow rate at the inlet (kg/s) | 27.07 | Inlet total temperature (K) | 1615.15 |
| Design mass flow rate at the outlet (kg/s) | 31.7 | Inlet flow angle (°) | 0.0 |
| Total pressure ratio | 4.80 | Outlet Mach number | 0.429 |
| Mass flow rate of cooling air (kg/s) | 4.63 | Blade tip clearance of $R_1$ and $R_2$ (%) | 1, 0.6 |

tip-leakage flow in turbomachinery. And the tip-leakage vortex is known to interact strongly with other vortices present in the tip region, such as passage vortex.[5] The interaction between the leakage vortex and the tip-side passage vortex gets stronger with the increase of flow turning angle and tip clearance.

Based on such knowledge a variety of passive and active flow control approaches have been tested as possible solutions to the tip-leakage problem in the published literature. Key and Arts[6] conducted a comparison of tip-leakage flow for flat tip and squealer tip geometries at high-speed conditions in a linear turbine cascade. Krishnababu et al.[7] also found a cavity tip is advantageous from both the aerodynamics and the heat transfer perspectives by providing a decrease in the amount of leakage, losses and average heat transfer to the tip. Nho et al.[8] investigated the effects of different blade tip shapes on total pressure loss of a linear turbine cascade experimentally. Van Ness II et al.[9] implemented active flow control using a blade-tip-mounted unsteady plasma actuator in a low pressure linear turbine cascade.

Axisymmetric endwall contouring is a type of passive control technique, and has become a promising approach in the reduction of endwall loss.[10–12] The axisymmetric endwall contoured reasonably could influence the local flow, and the vortex generation and development are inhibited by the acceleration throughout the cascade. Hence the aerodynamic loss is decreased. Unlike the blade tip shaping, little erodibility to the contoured endwall shape may be caused by the hot gas. So the question arisen here is whether such an idea could still work when implemented to the control of tip-leakage flow in turbine. Bohn et al.[13] did an axisymmetric-casing contouring to a four-stage turbine. It is a relative large off-set arc that across a whole turbine stage. Their numerical and experimental results indicates that the axisymmetric off-set arc endwall contour at the casing has positive influence on the radial distribution of the flow angle, the pressure field and the aerodynamic efficiency. In their research, the off-set arc endwall geometry aims to influence locally the radial pressure field and then the flow field in front of the rotor blade tip. And in their approaches of axisymmetric endwall contouring, the casing's contour is drawn inwards between two stages. But how does the contoured casing influence the tip-leakage flow if the contour is just on the casing of rotors? Wisler and Beacher[14] study the influence of recessed clearance over the rotor in a four-stage low-speed compressor and proper configurations could improve the efficiency by 1%–2% with some loss of stall margin. Offenberg et al.[15] presents their experiment on the understanding of the effect of shroud trenching on turbine performance. Efficiency improvement is achieved, but the research does not present the mechanism on how the shroud trenching reduces the tip-leakage loss. And the step-shape casing will cause additional loss.

So the present work aims to reduce the tip-leakage loss using the axisymmetric contouring on the casing of rotors in a two-stage unshrouded high pressure turbine (HPT) of aero-engine. The axisymmetric-casing contouring is obtained by introducing an axisymmetric off-set arc at the casing beyond the tip of rotor blade and the part of the blade stretches into the casing with the same arc shape. Then a numerical investigation is carried out to study the entropy generation rate in the tip region of the contoured and uncontoured casing turbine. And detailed analysis is done to understand the leakage flow in the tip gap and the mechanism by which the contoured casing influences this flow and the associated losses.

## 2. Model and computational method

### 2.1. Turbine in study

A two-stage unshrouded high pressure turbine of aero-engine is selected as the platform to investigate the influence of axisymmetric endwall contouring on blade tip-leakage flow and the associated loss. This turbine is a new design plan by our group according to the data of the two-stage high pressure turbine in NASA/GE Energy Efficient Engine (GE-E$^3$).[16,17] In this new design plan, the flow works with higher aerodynamic efficiency but fewer blades in each stage. So the loading in each blade of the turbine is higher. Details about the design are not the topic discussed herein and some of the main design parameters of this two-stage turbine are illustrated in Table 1. In Table 1, $R_1$ and $R_2$ are the rotor of first stage and second stage.

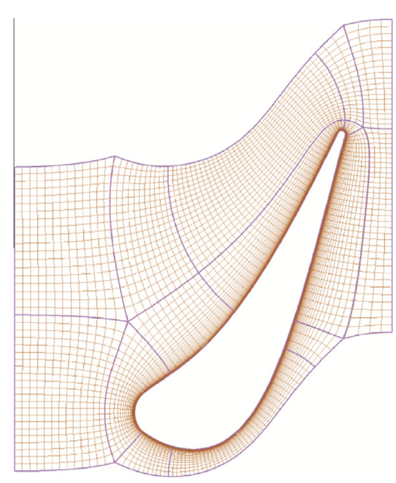

**Fig. 1** Grid topology of $S_1$.

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