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Comparative investigation of unsteady flow interactions in endwall regions of shrouded and unshrouded turbines

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ABSTRACT

The flow in turbomachinery is inherently unsteady, and the endwall losses are major sources of lost efficiency in turbine cascades. Therefore, the investigation of unsteady endwall flow interactions and the consideration of the effects into turbine design are valuable to improve the turbine performance. Comparative investigation into the physical mechanisms of unsteady endwall flow interactions of 1.5-stage shrouded and unshrouded turbines are performed by using a three-dimensional Navier–Stokes viscous solver. Emphasis is placed on how unsteady stator–rotor interactions affect turbine endwall secondary flows, and the feasibility of incorporating the unsteady endwall flow effects in turbine design is also discussed. The results show that unsteady interactions between upstream wake, tip leakage vortex/mixing zone and downstream passage vortex are the main factor affecting turbine endwall secondary flows. Unsteady interactions can reduce the radial vorticity of turbine endwall secondary flows, and the effects of these interactions on the streamwise vorticity of endwall secondary flows depend on upstream wake characteristics. The properly controlled unsteady interactions can reduce the size and intensity of endwall secondary flows, and thus improve the turbine performance. Because of the difference of turbine tip architectures, the periodic fluctuations of the flow in the shrouded turbine have smaller amplitude than those in the unshrouded turbine, and the shrouded turbine is of better unsteady performance than the unshrouded turbine.

1. Introduction

For modern turbine stages, the losses in the endwall regions could be as high as 30–50% of total aerodynamic losses in a blade row [1]. According to the flow characteristics in the endwall region, the endwall losses can be further divided into secondary vortex losses and tip leakage losses [2]. The tip leakage losses depend on whether the blade is shrouded or unshrouded, which are commonly used in turbomachinery design. Therefore, how to effectively control the endwall secondary flows and associated losses is very important for turbines.

Due to the fact that the endwall losses are so high, there have been numerous attempts and investigations performed to reduce the endwall losses and thus to improve turbine performances, such as bowed blades [3], endwall contouring [4], squealer tips [5], tip cooling injection [6], and geometry modifications of shroud cavities [7]. The above investigations are all limited to the steady flow; however, the flow in turbomachinery is inherently unsteady due to the relative motion of adjacent blade rows. Secondary vortex growth, boundary layer development, loss generation and heat transfer in turbines are all found to be strongly affected by the stator–rotor interaction. In order to further improve the aerodynamic performance of turbines, and to provide some reference for the choice of turbine architecture in specific application, it is necessary to well understand the unsteady endwall interaction mechanisms of shrouded and unshrouded turbines and to influence them.

Many researchers have reported the studies of the flow fields of three-dimensional unsteady interactions for single- or 1.5-stage unshrouded turbines, such as Binder et al. [8], Boletis and Sieverding [9], and Sharma et al. [10]. The experiment of Miller et al. [11] indicates that the interaction between a high-pressure stage and a downstream stator is not merely a simple two-dimensional interaction, and the inlet flow to a downstream stator is dominated by the upstream endwall secondary flow. Miller et al. [12] showed that high loss regions associated with the rotor hub passage vortex periodically disappear in a high-pressure turbine stage due to the stator–rotor interaction. Chaluvadi et al. [13] investigated the loss mechanism using half-delta wings installed on a rotating hub, in front of the stator row, to simulate an upstream rotor passage vortex. The loss measurements at the exit of the stator blade showed an increase in total pressure loss due to the delta wing vortex

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transport. The increase in loss was 21% of the datum stator loss, demonstrating the importance of this vortex interaction. The experimental result of Behr et al. [14] shows that the pressure field of the second stator row has an influence on the development of the tip leakage vortex downstream of the rotor. The vortex is modulated by the stator profile and shows variation in size and relative position to the rotor trailing edge (TE) when it stretches around the stator leading edge (LE), due to its interaction with the pressure field of the second stator LE. Qi et al. [15] experimentally and numerically investigated the unsteady interaction between upstream wake and secondary flow vortex, and the flow field at the exit of the turbine blade row shows a decrease in passage vortex strength and losses due to the upstream wake transportation. Besides, the transportation of upstream wake can suppress the development of the pressure side (PS) leg of horseshoe vortex and passage vortex, because of the "negative jet" effect of the wake.

However, only few researchers have up to now studied the time-resolved interaction of the shroud leakage flow and the main flow in shrouded turbines. Pfau et al. [16,17] examined the unsteady flow interactions within the inlet and outlet cavities of a turbine blade shroud labyrinth seal respectively. The results show that, the inlet and outlet cavity flows are highly three-dimensional. The toroidal vortex is found in the inlet cavity, which is subject to unsteady vortex stretching and tilting. In addition, the results reveal the uneven flow and the existence of high circumferential velocity within the entire exit cavity. Also, another interesting finding is that the fluid leaving the cavity is broken up into distinct oblique jets of low momentum embedded in the passage flow. Giboni et al. [18] examined the effect on the main-flow due to the leakage flow entering behind the rotor in a 1.5-stage axial turbine with a straight labyrinth seal on the rotor shroud. The experimental results indicate that the effect of shroud leakage flow is not uniform in the pitch-wise direction. Instead of a large rotor passage vortex, there is a small but intensive vortex downstream on the suction side (SS) of rotor wake. In agreement with the experimental data, the computational results show that even at realistic clearance heights the leakage flow can give rise to unsteady SS incidence on considerable parts of the downstream stator. This causes flow separation at the stator blades and a highly unsteady flow field at the second stator exit. It should be noted that, about the subject of shroud cavity interactions in shrouded turbines, it was addressed the first time by Denton and Johnson [19]; however, it is only in recent years that this subject has become the focus of much researches [20].

Because of the complexity of unsteady flow in the endwall regions, the unsteady interaction in turbines is still not well understood, especially in shrouded turbines. As for the comparative investigation of shrouded and unshrouded turbines, only some comparative steady flow investigations have been performed by Lampart [21] and Yoon et al. [22]. To the author's knowledge, no research papers have been published to describe the differences in unsteady flow interactions in endwall regions of shrouded and unshrouded turbines.

As previously mentioned, the flow in turbomachinery is inherently unsteady, due to the relative motion of adjacent blade rows, which inevitably has some effects on the turbine stage characteristics. From this consideration, the question arises: Is there any potential in improving the overall performance of turbines by making use of endwall interaction flows, or by considering the unsteady endwall flow effect in turbine design? In recent years, researchers have realized the potential of incorporating the unsteady flow effect in turbomachinery design, such as clocking effects [23], effects of wake recovery [24,25], and calming effects [26]. These studies have shown effectiveness in alleviating the negative impact of flow unsteadiness on turbine main flow fields. Therefore, the feasibility of incorporating the unsteady flow effect in the control of turbine endwall secondary flows can also be explored.

The numerical investigation presented in the paper has been made to clarify the physical mechanisms of unsteady endwall flow interactions of 1.5-stage shrouded and unshrouded turbines, and the results for shrouded and unshrouded turbine cases are compared to provide some reference for the choice of turbine architecture in specific application. Also, the feasibility of incorporating the unsteady endwall flow effect in design is discussed.

2. Turbine model

In this investigation, the blade geometry and flow conditions of the first three blade rows of two-stage high-pressure turbines in a modern engine [27] have been used to investigate the unsteady endwall flow interactions, as shown in Figs. 1 and 2. The rotor blades are twisted, and have a constant axial chord length of 28.7 mm and an aspect ratio of 1.39. It should be noted that the turbine blade has been scaled, in order to meet the need for unsteady computations. For the changed turbines, the aspect ratio for each row is 1.47, 1.21 and 1.4, and the blade exit angle for each row is 36.2, 63.5 and 67.2 degrees from axial direction; the flow coefficient and the stage loading for the first stage are 0.43 and 1.32 respectively, and the Zweifel load coefficient is 0.69, 0.75 and 0.68 for each row.

In order to make a fair comparison between shrouded and unshrouded turbines, the cases have the same outer casing diameter (732 mm); they also have the same tip clearance of 2.3% (1 mm) of rotor blade span [28,29]. In comparison to real applications, this value is relatively large, as gap of 0.7–1% blade span are commonly employed. However, the small inlet and exit cavities as well as the large gap were chosen in order to reduce the pure cavity-to-main flow interaction by increasing the leakage jet momentum and reducing main passage flow ingress into the shroud [30], thus facilitating the investigation of upstream wake-secondary flow interactions in shrouded tip endwall region. Besides, due to the large clearance gap, the effect of tip passage vortex inside the unshrouded rotor passage is greatly reduced, which also facilitates the investigation of the unsteady flow interaction in unshrouded tip endwall region.

3. Numerical approach

The numerical investigations presented in the paper were performed with steady and unsteady Navier–Stokes viscous solver ANSYS CFX 11.0 [31]. The solutions were obtained by solving the compressible Reynolds-Averaged Navier–Stokes equations using a finite volume technique. The spatial discretization of the equations uses second-order upwind scheme, and the temporal discretization uses second-order backward Euler scheme. In addition, the method of "dual time step" has been adopted to achieve a converging solution in time. In order to control the inner iterations in dual

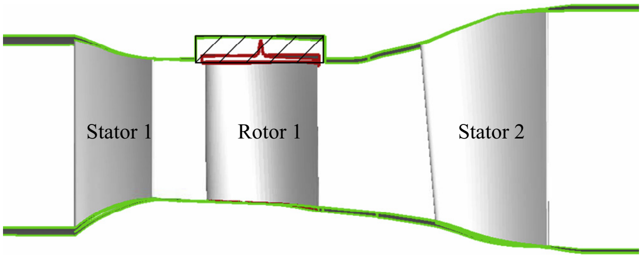

Fig. 1. Meridional view of a 1.5-stage turbine.