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Effects of axial gap and nozzle distribution on aerodynamic forces of a supersonic partial-admission turbine

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Abstract The turbine in an LH2/LOX rocket engine is designed as a two-stage supersonic partial-admission turbine. Three-dimensional steady and unsteady simulations were conducted to analyze turbine performance and aerodynamic forces on rotor blades. Different configurations were employed to investigate the effects of the axial gap and nozzle distribution on the predicted performance and aerodynamic forces. Rotor blades experience unsteady aerodynamic forces because of the partial admission. Aerodynamic forces show periodicity in the admission region, and are close to zero after leaving the admission region. The unsteady forces in frequency domain indicate that components exist in a wide frequency region, and the admission passing frequency is dominant. Those multiples of the rotational frequency which are multiples of the nozzle number in a full-admission turbine are notable components. Results show that the turbine efficiency decreases as the axial gap between nozzles and the 1st stage rotor (rotor 1) increases. Fluctuation of the circumferential aerodynamic force on rotor 1 blades decreases with the axial gap increasing. The turbine efficiency decreases as the circumferential spacing between nozzles increases. Fluctuations of the circumferential and axial aerodynamic forces increase as the circumferential spacing increases. As for the non-equidistant nozzle distribution, it produces similar turbine performance and amplitude-frequency characteristics of forces to those of the normal configuration, when the mean spacing is equal to that of the normal case.

1. Introduction

Supersonic turbines with partial admission are sometimes employed in rocket engines to avoid an extremely low blade height which would result in large secondary losses such as the tip leakage loss. In addition, partial admission

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configurations are commonly applied to control the power output and get higher efficiency in the control stages of power plants and industrial steam turbines. However, additional forms of loss exist in partial admission compared with full-admission turbines, such as the mixing loss generated in the interface regions between the low-energy dead flow and the high-energy through flow, which significantly influences the efficiency.[1] Furthermore, circumferential non-uniformity is increased due to partial admission. The flow in a turbomachine is highly unsteady because of the interaction between adjacent rows due to the effects of wakes.[2,3] In a partial-admission turbine, rotor blades periodically pass through flowing regions as well as regions of no flow, inducing strong flow-exciting forces besides vane wakes, which may result in high cycle fatigue.[4] Rotor blade cracks once occurred in turbopump tests for some liquid rocket engines designed with a partial-admission turbine, and the failure is believed to be caused by exciting forces. It is certainly necessary to investigate the unsteady flow and aerodynamic forces in partial-admission turbines.

Experimental investigations and theory analysis of partial admission have been conducted by several researchers.[5–9] Numerical simulation has also been a powerful approach widely used by researchers. Full 360° Computational Fluid Dynamics (CFD) models and 3-Dimensional (3D) transient simulations are usually required, and sometimes multistage simulation is needed, which all make numerical investigations with high computational costs.[10] 2-Dimensional (2D)[1,11] and quasi-3D[12] simulations were usually conducted in the past. With the development of CFD and the improvement of computers, 3D transient numerical simulations for investigations of partial admission have been widely conducted. Effects of the axial gap between the first-stage stator and rotor and multiblocking on the performance of partial-admission turbines were numerically studied by Hushmandi and Fransson.[13] They illustrated that reducing the axial gap produced a better efficiency at the first stage, but the overall efficiency at the second stage was decreased. Numerical simulations were conducted for a steam turbine with different degrees of partial admission by Qu et al.[14], and they pointed out that the unsteady computational result was more accurate to analyze the flow of the control stage. Newton et al.[15] investigated the sources of loss in a turbine with both full and partial admission numerically, and evaluated the distribution of loss with entropy production. From these previous investigations about partial admission, we can see that steam turbines has usually been studied and the turbine aerodynamic performance has mostly been focused on. However, unsteady forces on rotor blades for a rocket engine turbine have been investigated by relatively few studies, especially a turbine with partial admission. Jöcker et al.[16] numerically studied the aerodynamic excitation mechanisms due to the unsteady stator-rotor interaction in a supersonic turbine for a rocket engine turbopump. Hudson et al.[17] experimentally measured and numerically simulated the surface pressure on a rocket engine turbine blade. Tokuyama et al.[18] conducted numerical simulation for a partial-admission turbine used for a rocket engine. The blade scaling procedure was adopted, which resulted in a simulation with one third of full passages. The unsteady aerodynamic force was analyzed. They showed that unsteady force components appeared in wide frequencies. Using a genetic algorithm, the partial admission of a supersonic turbine was optimized by Tog and Tousi.[19]

The turbine in the current study is used for an expander cycle LH2/LOX rocket engine. It is a two-stage supersonic turbine with partial admission. A first-stage rotor blade cracked in a test. Besides processing defects, the excitation produced by the partial admission configuration and supersonic nozzles was considered to result in the failure. Therefore, the unsteady flow in a full-annulus turbine was numerically investigated in this paper to study the unsteady aerodynamic forces. Furthermore, effects of the axial gap and nozzle distribution on the turbine performance and aerodynamic forces were studied, in order to search for a possible method to reduce the excitation. Configurations with different equal circumferential spacings between nozzles and unequal circumferential spacings were analyzed to study the effect of the nozzle distribution on the turbine performance and unsteady forces on rotor blades. Configurations with various axial gaps between nozzles and the first-stage rotor were analyzed to investigate the influence of the axial gap on the turbine performance and aerodynamic forces.

2. Computational procedures

2.1. Fundamental equation

Reynolds time-averaged Navier-Stokes equations are solved by commercial CFD software of ANSYS-CFX. The general form of governing equations for the compressible viscous unsteady flow in a Cartesian coordinate is expressed as follows:

$$\frac{\partial(\rho\phi)}{\partial t}+\mathrm{div}(\rho\boldsymbol{U}\phi)=\mathrm{div}(\Gamma_\phi\,\mathrm{grad}(\phi))+S_\phi \tag{1}$$

where ρ is density, ϕ is the general variable for different equations, t is time, $\boldsymbol{U}$ is velocity, Γ_ϕ is the general diffusion coefficient, and S_ϕ is the general source term. Conservation equations for mass, momentum, and energy can be obtained by setting ϕ to 1, u, v , w, and h, where u, v, w are velocity components, and h is enthalpy. Turbulence models can be obtained when setting ϕ to turbulence kinetic energy k and turbulent frequency ω. The ideal gas equation of state is adopted for enclosure.

The $k-\omega$ based Shear Stress Transport (SST) turbulence model was employed in this study, since it can give highly accurate predictions of the onset and the amount of flow separation under adverse pressure gradients.[20–22] The SST model combines the advantages of the $k-\omega$ model in the near-wall region and the $k-\varepsilon$ model in the bulk domain, and accounts for the transport of the turbulent shear stress. The proper transport behavior can be obtained by a limit to the formulation of the eddy-viscosity as:

$$\nu_{\mathrm{t}}=\frac{a_1 k}{\max(a_1\omega, SF_2)} \tag{2}$$

where a_1 is equal to 5/9, S is an invariant measure of the strain rate, and F_2 is a blending function expressed as:

$$F_2=\tanh(\mathrm{arg}_2^2) \tag{3}$$

$$\mathrm{arg}_2=\max\left(\frac{2\sqrt{k}}{\beta'\omega y},\frac{500\nu}{y^2\omega}\right) \tag{4}$$

where $\beta'=0.09$, y is the distance to the nearest wall, and ν is the kinematic viscosity.

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