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Numerical analysis for impacts of nozzle end-clearances on aerodynamic performance and forced response in a VNT turbine

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Abstract It has been well known that nozzle end-clearances in a Variable Nozzle Turbine (VNT) are unfavorable for aerodynamic performance, especially at small openings, and efforts to further decrease size of the clearances are very hard due to thermal expansion. In this paper, both the different sizes of nozzle end-clearances and the various ratios of their distribution at the hub and shroud sides were modelled and investigated by performing 3D Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) simulations with a code of transferring the aerodynamic pressure from the CFD results to the FEA calculations. It was found that increasing the size of the nozzle end-clearances divided equally at the hub and shroud sides deteriorates turbine efficiency and turbine wheel reliability, yet increases turbine flow capacity. And, when the total nozzle end-clearances remain the same, varying nozzle end-clearances' distribution at the hub and shroud sides not only shifts operation point of a VNT turbine, but also affects the turbine wheel vibration stress. Compared with nozzle hub clearance, the shroud clearance is more sensitive to both aerodynamic performance and reliability of a VNT turbine. Consequently, a possibility is put forward to improve VNT turbine efficiency meanwhile decrease vibration stress by optimizing nozzle end-clearances' distribution.

1. Introduction

The past decade has seen that the emission standards for various types of vehicles have been becoming more stringent. To achieve less emission, car manufacturers are attempting to downsize an internal combustion engine that can provide the same power of a large engine by adding a boosting device, e.g. turbochargers.[1] To better acceleration and deliver more power across a wider range, a Variable Nozzle Turbine

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(VNT) has been developing and applied.[2] A common method of variable nozzle in a radial turbine is the use of the pivoting vanes that are mounted on a flat plate. These vanes are connected with spindles, sometimes together with handles, to achieve the function of rotating axially. Between the flat plate and nozzle vanes, nozzle end-clearances have to be designed.

Efforts to reduce the nozzle end-clearances' size have been doing, and so far the size has been successfully decreased in advanced VNT turbos. But the unfavorable effects of the clearances are still significant and further decreasing the size will be very hard, since the nozzle vanes would get stuck due to thermal expansion. The temperature of exhaust gas is often more than 900 °C for a diesel engine and beyond 1000 °C for a gasoline engine. In addition, complicated sulfide from exhaust gas moves outward from wheel inducer to nozzles under the action of centrifugal force, and then is possible to stick the nozzle vanes as the clearances are too small.

It has been reported that the presence of the nozzle end-clearances usually has unfavorable effects on aerodynamic performance of a VNT turbine. Hu et al.[3] performed numerical simulations on a VNT turbine to study the nozzle end-clearances' effect on turbine performances and revealed that the presence of nozzle end-clearances deteriorated turbine performances, especially at small open condition. Walkingshaw et al.[4] carried out numerical simulations of the flow fields in a highly off-design VNT turbine and indicated that the leakage vortices changed the circumferential distribution of the approaching flow to the rotor and then deteriorated aerodynamic performance. The relationship between the nozzle end-clearances and the turbine performance was also focused by Tamaki et al.[5,6] Besides the aerodynamic performance, the high cycle fatigue is one of the critical issues that the development of an advanced VNT turbine has to address. Shock waves, one of the contributors to the high cycle fatigue failure, weigh heavily on the turbine wheel blade vibration and, sometimes, could seriously damage a turbine wheel, as shown by Chen.[7] The intensity of the shock wave was proved to be closely related with nozzle end-clearances in a VNT turbine.[8] Therefore, the nozzle end-clearances must have an effect on turbine wheel reliability. In fact, the nozzle clearance leakage flow is also able to directly interact with a turbine wheel and then causes it to vibrate.[9,10]

Though it has been reported that the nozzle end-clearances are closely related to the turbine performance, the relationship between the forced response of turbine wheel and the changed clearances, i.e. increased clearance size and different distribution, is not fully clear. If the nozzle shroud clearance has a significantly different effect on a VNT turbine from the hub clearance, it will provide a possibility to further improve a VNT turbine in both the aerodynamic performance and the reliability by optimizing the more sensitive clearance, instead of the hard effort to further decrease the size of total nozzle end-clearances.

In this paper, a VNT turbine was first modeled and simulated by a 3D steady Computational Fluid Dynamics (CFD) method to validate computational mesh, and then the VNT turbine model with various nozzle end-clearances were predicted by both steady and unsteady CFD methods. After CFD simulations, the information about aerodynamic excitation pressure on a wheel blade surface was transferred from the CFD results to the Finite Element Analysis (FEA) calculation by interpolation so that the harmonic response could be predicted and analyzed. Finally, an optimized nozzle end-clearances' distribution with high turbine efficiency and low forced response was suggested.

2. Research model

The research model is a VNT turbine. In order to reduce the requirement of CFD simulations, the volute was neglected. This simplification should have little influence on the conclusions stated in this paper, since the flow is guided and redistributed in crossing the nozzles. Therefore, the model used just consists of variable nozzles vanes and a mixed-flow rotor.

Fig. 1 shows the meridional view of a VNT turbine with detailed illustrations of nozzle end-clearances, and two types of nozzle vanes. Inside the clearances, the spindle and the handle of a nozzle vane are not illustrated.

The pivoting nozzle vanes are often fixed and controlled by a spindle or a combination of a spindle and a handle. If the spindle is located round the center of a vane, the handle will be not needed, whereas if it is located near trailing edge of a vane, the handle is often designed and installed near the vane's leading edge to well control the vanes' setting angle, as shown in Fig. 1.

Regardless of the control styles, VNT turbine always requires the presence of nozzle end-clearances to achieve the relative movement between nozzle vanes and the flat plates (endwalls). Herein, the nozzle shroud clearance is marked with C_{shroud} and the clearance on another side is represented by C_{hub}, as shown in Fig. 1.

In order to clearly identify the research models used, the investigated VNT turbine with various nozzle end-clearances is numbered and listed in Table 1. The letter, h, stands for the normal height of the nozzle end-clearance at each side of a VNT turbine product, and is about 2 percent of the span of flow passage from the hub wall to the shroud one.

3. Numerical schemes

3.1. CFD model

A fully automatic hexahedral grid generator was used to generate the computational mesh for the whole flow field. Multi-block Structured Meshing with an O4H topology including 5 blocks was used to discrete the channels, as shown in Fig. 2. The skin block was an O-mesh surrounding the blade and the H-mesh was applied in inlet, outlet, up and down blocks. The mesh inside the hub and shroud clearances was created using a butterfly topology. The number of grid points had to be adjusted for various clearance sizes to keep a good mesh quality under the condition of the same first cell length.

The subsonic inlet condition with total pressure, total temperature, velocity angles and turbulent viscosity were specified at the inlet boundary of the computational domain. At outlet boundary, a radial equilibrium technology was used. With this, the outlet static pressure was imposed on the given radius and integration of the radial equilibrium law along the spanwise direction permitted to calculate the hub-to-shroud profile of the static pressure. Therefore, a constant static pressure would be imposed along the circumferential direction. On the solid surface, the adiabatic walls were used and the velocity vector vanished. The rotational speed of the unsteady simulations

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