Numerical Study of the Blade Sweep and Lean Effects on an Axial Supersonic Impulse Turbine Flow Field and Performances

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1. INTRODUCTION & OBJECTIVE

We are studying on improving the performance by applying the three-dimensional design element to the rotor blades of high pressure supersonic impulse turbine that drives turbo pump of liquid rocket engine.

The implementation of three-dimensional geometrical features such as blade sweep or lean to improve the gas turbine efficiency has been studied in recent decades. A review of the techniques usually used in the industry is well presented by Denton and Xu [1]. The three-dimensional blade design in numerical researches carried out so far is, however, limited to subsonic or transonic fan/compressor using steady state calculation. There have been few known researches on the swept and leaned rotor blade effects for a supersonic impulse turbine so far.

In this paper, based on the shape of a rotor blade of a turbopump turbine designed in the past, a three-dimensional shape is applied to a first stage rotor blade through a stacking line change such as sweep and lean. The three-dimensional unsteady RANS (URANS) simulation was performed on the small supersonic axial turbine having rotor blade sweep angles (±15°) and lean angles (±15°) including no sweep & lean angle (0°) as a datum. After performing the flow analysis, the changes in the turbine performance characteristics for each design element were carefully examined and the results were summarized.

Model turbine used for this study is the partial admission supersonic axial turbine consists of 21 converge-diverge nozzles having rectangular shaped exit and 100 impulse type shrouded rotors with flat blade tip. The exit velocity of nozzle is designed to reach Mach 2.3.

The definition of sweep and lean angle are illustrated in fig.1.

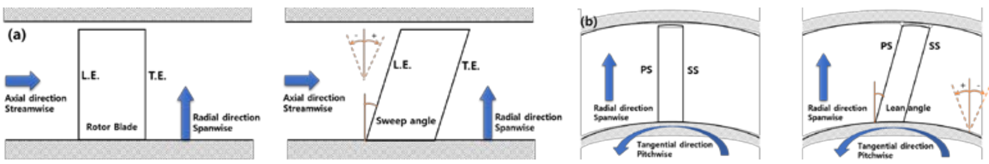

Fig. 1 Definition of (a) blade sweep and (b) blade lean

All numerical analyses were carried out by using FLUENT™ with density-based coupled solver. Quantities at cell faces of finite volumes are discretized with 2nd-order upwind scheme and implicit method were adopted for temporal discretization. Turbulence was modeled using k-ω SST model. For unsteady calculation, the sliding mesh model (SMM) was utilized at nozzle-rotor interface.

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2. RESULTS & CONCLUSION

(1) Sweep; In our previous study [2], the sweep effects applied to a supersonic turbine rotor had been investigated. The incidence angle at rotor inlet plane tends to reduce as the sweep angle increases. The backward sweep model was consequently shown the best result among the sweep models and datum. And also the rotor blade sweep can affects the average Mach number and its distribution over the rotor passage. It was found that the sweep angle had a considerable effect on the mass flow rate of leakage flow through tip clearance. It was observed that the flow loss in the region from hub wall to about 30% span of backward sweep model is less than the other models. As a result, there was a total to static efficiency increases of +0.9% for backward sweep model compared to datum.

(2) Lean; There are various researches on lean and bow effects on the performance of compressors and turbines, but there is not much study on the performance of supersonic turbines. Marcu et al.[3] had attempted to minimize the dynamic load at the trailing edge of the vane by applying a negative lean 20 ° to the vane through the optimization technique using CFD in the study of NASA's J-2X engine design. The negative lean model was shown the best result among the lean models and datum. In the case of leaned blade, it was found that the loss distribution varies widely on the hub region. Negative lean model was slightly less than datum from hub to the midspan, and positive lean model showed the most prominent loss in the hub region among these three models. Regarding the total to static efficiency, there was no significant change in negative lean model and decreases of 1% or more in positive lean model compared to datum.
In conclusion, a three-dimensional shapes through a stacking line changes such as sweep and lean were applied to a rotor blade based on the existing turbopump turbine designed in the past in this paper. After performing the 3D unsteady flow analysis using CFD, the effects on a turbine flow field and performance characteristics by each design element were examined.

For the five models of forward sweep, backward sweep, positive lean, and negative lean including datum case as a reference model, the relative Mach number contours of the rotor inlet, the circumferential mean constant pressure distribution of the rotor inlet and outlet, the relative incident and outlet angles, and the entropy distribution at the rotor outlet and so on. Each design parameters affects the performance of a turbine as shown in fig. 2, and these results can be used as data of the three-dimensional blade design for turbo pump turbine to improve its performance.

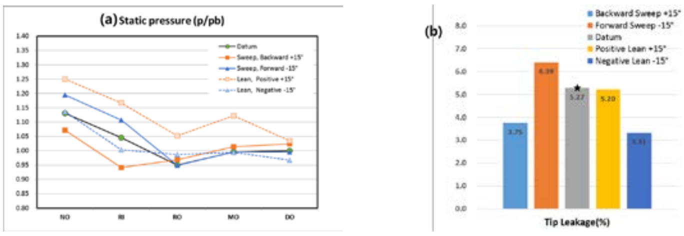

Fig. 2 Changes of performance (a) static pressure at each sections (b) tip leakage mass flow rate

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