A Study on the Effect of Inlet Boundary Condition on Flow Characteristics of a Supersonic Turbine

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Abstract

The inlet boundary condition of computations about the supersonic turbine flow is commonly applied as far-field inlet boundary condition with specified velocity. However, the inflow condition of supersonic turbine is sometimes affected by the shocks or expansion waves propagated from leading edges of blade. These shocks and expansion waves alter the inlet boundary condition. In this case, the inlet boundary condition can not be specified Therefore, in this paper, numerical analyses for three different inlet conditions - fa-field inlet boundary condition, inlet boundary condition with a linear nozzle and inlet boundary condition with a converging-diverging nozzle - have been performed and compared with experimental results to solve the problem. It is found that the inlet condition with a linear nozzle or a converging-diverging nozzle can prevent changing of inlet boundary condition, and thus predict more accurately the supersonic flow within turbine cascade than a far-field inlet boundary condition does.

Key Word : Supersonic Turbine, Fine Turbo, Inlet Boundary Condition with a Nozzle, Far-Field Inlet Boundary Condition, Partial Admission

Introduction

Turbo-pump system adopts a partial admission axial turbine which drives pump. A partial admission axial turbine often generates very high power output even though it is small and light. It is therefore widely used for power generation of various flying vehicles. The turbine of a turbo-pump system is usually operated at supersonic condition due to its high loading characteristics. While flow and performance characteristics of general axial turbines are well known by various experimental and computational studies, those for partial admission axial turbines are not disclosed because of complicate flow patterns such as shocks, separations and shock-boundary interactions. Therefore it is very difficult to estimate the performance or to design the turbine well.

In this situation, investigations for flow characteristics within supersonic turbine are very important for development of a turbo-pump system. However, the previous studies used with far-field inlet boundary condition could not predict accurate flow and performance characteristics.

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Therefore, in this paper, the flow within supersonic cascades with three different inlet conditions have been numerically investigated by using Fine Turbo, a commercial CFD code, and then compared with experimental results.

Results and Discussions

A general methodology and its problem

Computation about supersonic flows within turbine cascades is usually performed with the computational domain as shown in Fig. 1. Boundaries of the domain consist of suction surface, pressure surface, inlet, outlet and periodic conditions. The inlet boundary condition is commonly applied as far-field inlet boundary condition with specified velocity. However, the inflow condition of supersonic turbine is sometimes affected by the shocks or expansion waves propagated from leading edges of blade. These shocks and expansion waves alter the inlet boundary condition. In this case, the inlet boundary condition can not be specified.

In this paper, firstly, numerical analyses have been performed with far-field inlet boundary condition to confirm the effect of the shocks or expansion waves and the change of inlet boundary condition. Computations have been performed by Fine Turbo. Cascades used in this computations are supersonic cascades designed for a turbo-pump system. A H-type 273×63 grid was used. Velocity, static pressure and static temperature were specified on the inlet boundary condition and static pressure was enforced on the outlet boundary condition. 3 level multi-grid method and initialization method were used to reduce computation time.

Table 1. shows values of inlet boundary condition. Resultant values of the inlet boundary condition are shown to be different from the inlet boundary values specified initially. The difference was occurred by shocks or expansion waves propagated from leading edge of blades. It is thereby found that it is impossible to accomplish analysis of flow and performance characteristics at intended boundary values with far-field inlet boundary condition.

Therefore, in this paper, a linear nozzle or a converging-diverging nozzle was located in front of cascades to prevent from changing inlet boundary condition.

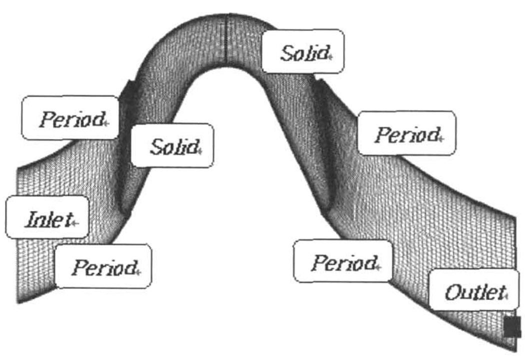
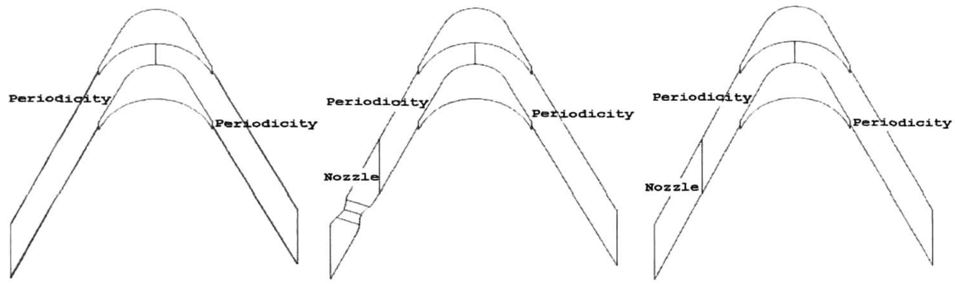


Fig. 1. Geometry & grid system with a far-field inlet boundary condition

Table 1. The difference between initial and resultant values of inlet boundary condition

Initial inlet boundary condition		Resultant inlet boundary condtion
β_1=15.00°	M_1=2.563, T_1=832K, p_1=0.17Mpa	β_1=15.68°, M_1=2.563, T_1=902K, p_1=0.31Mpa
β_1=16.89°		β_1=16.08°, M_1=2.066, T_1=957K, p_1=0.45Mpa
β_1=20.00°		β_1=15.69°, M_1=2.561, T_1=1205K, p_1=2.03Mpa



(a) (b) (c)

Fig. 2. The geometric condition of a far-field inlet boundary condition (a), inlet boundary condition with a linear nozzle (b) and with a converging-diverging nozzle (c)

Three different inlet boundary condition

Firstly, in a far-field inlet boundary condition, there is no additional nozzle in front of cascades as shown in Fig. 2 (a). Supersonic velocity and static pressure are enforced as the inlet boundary condition.

Next, in the method of inlet boundary condition with a linear nozzle, a linear nozzle is located in front of cascade as shown in Fig. 2 (b). Supersonic velocity and static pressure are also applied to the inlet boundary condition. The value of velocity and pressure is equivalent to that of velocity and pressure to produce a supersonic flow which is identical with the inflow of far-field inlet boundary condition. In addition, the condition of nozzle wall is confined as slip-wall condition to remove the viscose effect on nozzle wall.

Finally, in the method of inlet boundary condition with a converging-diverging nozzle, a converging-diverging nozzle is located in front of cascade as shown in Fig. 2 (c), total temperature and total pressure are thus applied to the inlet boundary condition. Area ratio of inlet and throat of nozzle, total pressure and total temperature are enforced to produce the same supersonic flow as the inflow of far-field inlet boundary condition, and the condition of nozzle wall is also applied as slip-wall condition to remove the viscose effect on nozzle wall.

The effect of inlet boundary conditions

In this section, numerical analyses for three different inlet conditions have been performed to investigate whether inlet boundary condition was changed. In addition, the numerical results were compared with experimental results of C. D. Colclough[1] and J. J. Cho[5] to investigate accuracy of these results.

Firstly, numerical results were compared with Colclough's experiment about supersonic flow within supersonic cascades with the wind tunnel. The cascade used in the test was designed to satisfy design conditions, A inlet Mach number of 1.366 and a turning angle of 116° as shown in Fig. 3. Operating gas of the wind tunnel was air of flow rate of 0.75 lb/s and static pressure of 66psi. Computations have been performed for the corresponding cascades and flow conditions. A linear nozzle or a converging-diverging nozzle were designed and located in front of cascades to identify with the inflow condition of experiment, Mach number of 1.5, incidence of +9° and static pressure of 66psi.

Fig. 4 (a) shows a Schlieren image of Colclough's experiment for incidence of +9° and Mach number of 1.5. A weak detached shock wave caused by a slight bluntness of the leading edge of 1st blade is observed. Oblique shocks occurred at leading edge of 1st and 2nd blade are propagated upstream and downstream. The upstream shocks are reflected on a upper nozzle wall and then enter into 3rd passage (the flow passage between the suction side of 3rd blade and the pressure side of 4th blade), and the downstream shocks are bent by designed expansion waves occurred at 35 percent of the chord on the suction side. Separation bubbles are also occurred at

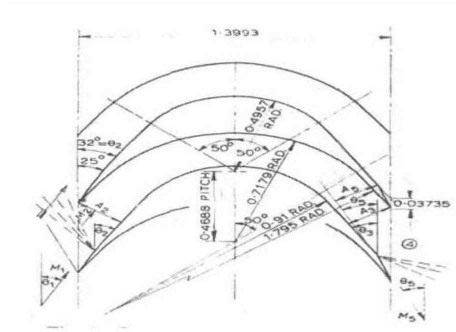
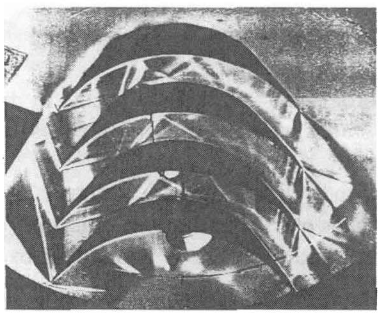
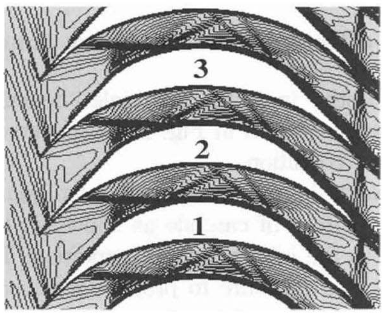


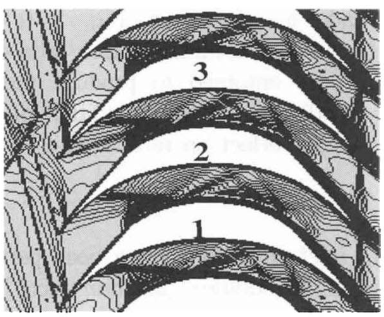
Fig. 3. Supersonic blade profile : Colclough's cascade



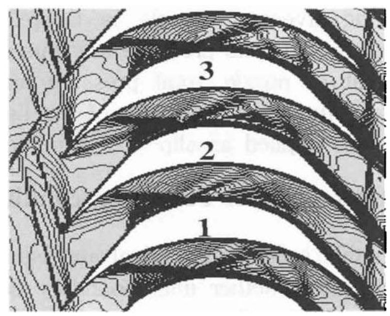
(a) Schlieren image of experiment



(b) Mach contours for far-field inlet condition



(c) Mach contours for a linear nozzle



(d) Mach contours for a converging-diverging nozzle

Fig. 4. Experimental and computational results at +9 degree incidence and Mach 1.5

about 35 percent of the chord on the suction surface, which is caused by shock-boundary layer interaction.

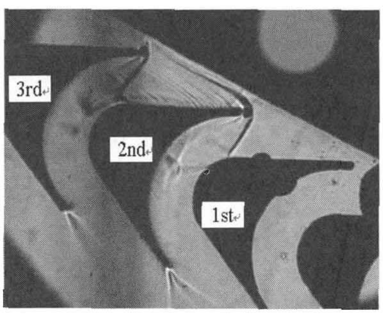
Fig. 4 (b) shows Mach number contours computed with far-field inlet boundary condition. Resultant values of inlet boundary condition are changed from incidence of +9° and Mach number of 1.5 to incidence of +1.5° and Mach number of 1.575. Due to the decrease of incidence angle, oblique shocks formed at leading edge are much weaker than those of experiment and are disappeared immediately through offsetting with expansion waves generated at 5 percent of the chord on suction surface. However a weak detached shock is not observed due to the sharp edge of computational geometry, which is different from the model geometry used in experiment. Separation bubbles are not observed in the computation. Comparing the result with experimental result, the flow patterns for far-field inlet boundary condition are different from those of experimental result.

Fig. 4 (c) shows Mach number contours computed for inlet boundary condition with a linear nozzle. Oblique shocks are clearly observed at the leading edge of the 1st and the 2nd blade. The upstream shocks are reflected on the nozzle wall and enter into the 3rd passage, and the downstream shocks are bent by designed expansion waves formed at 35 percent of the chord on the suction surface. The flow is also separated at the 35 percent of the chord on the suction surface by shocks and boundary-layer interaction. Comparing the flow patterns of experimental results, though there is a little difference of oblique shocks, the results are agree reasonably with experimental results. The little difference seems to be caused not by changing inlet boundary values but by expansion waves attached at the end of a nozzle. Cascades were located in the back of nozzle due to the application of the periodic condition for modeling full admission turbine, while cascades in the experiment were located inside the nozzle. For that reason, the expansion waves are formed behind nozzle and affected the flow entering into channel.

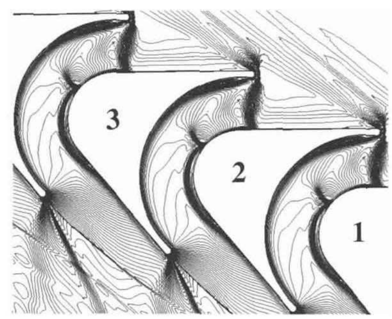
Fig. 4 (d) is the numerical results for inlet boundary condition with a converging-diverging nozzle. Flow characteristics including separation and shock patterns of the result are very similar to those of a result for inlet boundary condition with a linear nozzle. The result of inlet boundary condition with a converging-diverging nozzle is more accurate than that with a far-field inlet boundary condition.

Next, numerical results were also compared with J. J. Cho's experimental results. Cho investigated supersonic flow within supersonic cascade with a small supersonic wind tunnel designed to produce supersonic flow of Mach number of 2.0. The wind tunnel was driven by nitrogen gas of total pressure of 200 psi and total temperature of 293K.

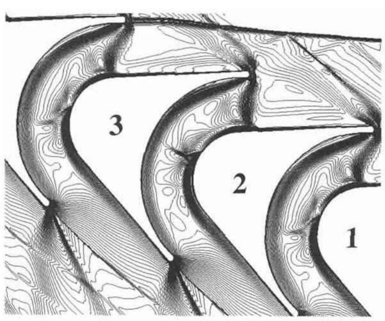
Fig. 5 (a) shows a shadow-graph of experimental result. Detached shocks are generated at



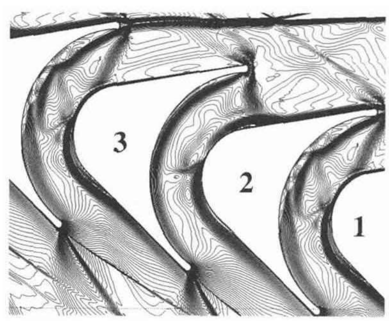
(a) Schlieren image of experiment



(b) Mach contours for far-field inlet condition



(c) Mach contours for a linear nozzle



(d) Mach contours for a converging-diverging nozzle

Fig. 5. Experimental and computational results for inlet total pressure of 200psi

the leading edge of the 2nd and the 3rd blade and spread into flow passages. The shock occurred at the 3rd blade is bent by a oblique shock formed at 40 percent of the chord on suction surface of the 2nd blade. Flow separations are clearly observed along the pressure surface of the 2nd blade and at 40 percent of the chord on the suction side of the 2nd blade. Additional shocks are also observed in middle of the flow passages.

Fig. 5 (b) shows Mach contours of numerical result computed with a far-field inlet boundary condition. Computed inlet boundary values are also changed from flow the angle of 66° and Mach number of 2.0 to flow angle of 62.33° and Mach number of 1.67. The change of inlet values get detached shocks to be much weaker than those of the experimental results as shown in Fig. 6 (a). Flow separation bubbles on the suction surface of the 2nd blade are observed from almost a half of the chord, which may be caused by the normal shocks. As we can see, flow and shock pattern of the result is different with that of the experimental result.

Fig. 5 (c) shows Mach number contours of numerical result with a linear nozzle. First, detached shocks are occurred at the leading edge of blades, and these shocks spreading into flow passage are bent by oblique shocks formed at 40 percent of the chord on suction side. Small separations are observed from the 40 percent of the chord on suction side. The computational result is a little different with the experimental result. However, this seems to be caused not by the change of inlet boundary values but by wake occurred from the end of nozzle. The wake is caused by the periodic conditions, which affects flows entering into channels. Comparing flow characteristics, the results computed with a linear nozzle are more similar than that of the numerical result with a far-field inlet condition.

Fig. 5 (d) is the numerical result for inlet boundary condition with a converging-diverging nozzle inlet boundary condition. Flow separation is clearly observed from 35 percent of the chord on the suction side of the 2nd blade, which is caused by the shock and boundary-layer interaction. Oblique shock is also observed in middle of the 2nd flow passage. Though the result have a little difference with experimental result, the flow characteristics are very similar to those of experimental result.

According to the previous comparisons between the numerical results and the experimental results, we can found that the computational results for inlet condition with a linear nozzle or a converging-diverging nozzle predict more accurate flow characteristics than those of far-field inlet boundary condition do.

Conclusion

In this paper, first, computation with a general methodology, a far field inlet boundary, have been performed to confirm a crucial problem of the method. It is found that the change of inlet boundary conditions is occurred by obliques shocks or expansion waves propagated from the leading edge of blades and that accurate prediction of flow and performance characteristics can not be accomplished because of the ambiguous inlet condition.

In this study, numerical analyses for three different inlet conditions have been performed, and compared between computational results and experimental results. Comparing the flow characteristics including separation and complicate shock patterns for inlet boundary condition, it is found that computational results with a linear nozzle or a converging-diverging nozzle can prevent the change of inlet boundary value and predict more accurate flow characteristics than those of far-field inlet boundary condition.

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