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Development Status of a Fore-Loaded Turbine Blade

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ABSTRACT

To reduce specific fuel consumption and to suppress CO2 emission with reduced engine weight is one of the requirements for environmentally-friendly next generation supersonic propulsion systems.

This research and development aims to develop a technology for designing a turbine blade row with a lower number of blades corresponding to composite materials. The new concept blade aerofoil, named "Fore-Loaded turbine blade", is applied to reduce a number of turbine blades.

This paper describes the development status of the Fore-Loaded turbine blade. At first, the Fore-Loaded turbine blade was applied to nozzle vanes of the first trial test turbine. This first trial turbine was designed and tested with the aerodynamic test equipment. As the second trial test turbine, the Fore-Loaded turbine blade was applied to also rotor blades, and designed. The second trial turbine will be tested with the test equipment.

INTRODUCTION

Next generation super sonic propulsion systems are required environmentally compatibility. Thereby the project on research and technology development of environmentally compatible propulsion system for next-generation supersonic transport (ESPR project) was initiated in Japan fiscal year (JFY) 1999 with the New Energy and Industrial Technology Development Organization (NEDO) support under Ministry of Economy, Trade and Industry (METI) of Japan. One of the ESPR project objectives is to suppress CO2 emission by 25% of 1999 technology level.

To reduce engine weight is expected to reduce specific fuel consumption and to suppress CO2 emission. To reduce the engine weight, composite materials such as 3-D fiber reinforced materials and technologies of applying a lightweight structure are necessary. In addition, reducing the number of turbine blades also contribute to reduction of engine weight.

This research aims to develop a technology for designing a turbine blade row with lower number of blades. The blade row with lower number of blades will not only contributes to reduce engine weight, but also constructs easily with composite materials, which contribute more weight reduction, because pitch width of the blade row is expanded. Besides, the blade row with lower number of blades contributes to reduction of stress to disk etc. Consequently, the weight of these components will be reduced.

In case the number of blades with a conventional velocity distribution (called "Conventional turbine blade" in this paper) is reduced for a stage work, strong velocity gradient on the blade surface and strong shock wave in flow passage are appeared. Consequently, aerodynamic loss of the blade row is sharply increased.

In this paper, the new concept aerofoil with unique velocity distribution on suction surface of a blade was applied so as to reduce the number of turbine blades. The new turbine blade was named "Fore-Loaded turbine blade". The Fore-Loaded turbine blade, where a velocity distribution peaks at the front half of blade suction surface, was optimized the velocity distribution on the blade surface so that increment of aerodynamic loss caused by the strong deceleration of velocity on the blade surface or strong shock wave in flow passage was minimized. As a result, work per blade could be increased and, in turn, the number of blades could be reduced without extreme increment of aerodynamic loss.

Two dimensional high-load characteristics of the Fore-Loaded turbine blade in the linear cascade test have been confirmed by K. Hashimoto etc. In this paper, Fore-Loaded turbine blade was applied to actual three dimensional turbine blades, and aerodynamic tests on the Fore-Loaded test turbine was conducted to obtain and evaluate the performance data.

RESEARCH OBJECTIVE AND SCHEDULE

The target technology aims at reducing the number of turbine blades by approximately 30% without losing existing the performance of a turbine stage by applying the Fore-Loaded turbine blade.

In JFY 1999, the specification of the first trial turbine, where the Fore-Loaded turbine blade was applied to only nozzle vanes, was determined.

In JFY 2000, detailed aerodynamic design of the first trial turbine was conducted. And the first trial turbine blades were manufactured. In addition, the aerodynamic test equipment was designed and fabricated.

In JFY 2001, aerodynamic tests on the first trial turbine were conducted to obtain and evaluate the performance data.

In JFY 2002, based on the assessment of the test results, the specification of the second trial turbine, where the Fore-Loaded turbine blade was applied to also rotor blade, was determined, and detailed aerodynamic design of rotor blade was conducted.

In JFY 2003, aerodynamic tests on the second trial turbine will be conducted to obtain and evaluate the performance data.

FORE-LOADED TURBINE BLADE

The characteristics of the Fore-Loaded turbine blade are followings,

- Between the leading edge and 10-30% of the blade suction surface, the flow near the blade surface is accelerated rapidly.

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Behind the location of the maximal velocity, it is decelerated gradually until trailing edge.

- The minimal velocity is located on 10-30% of the blade pressure surface from leading edge.
- The blade profile has a blunt leading edge

The two dimensional Fore-Loaded turbine blade and the conventional turbine blade were tested with the linear cascade test equipment to obtain this aerodynamic performance by K. Hashimoto etc. The high load characteristic of Fore-Loaded turbine blade was confirmed by the comparison of the performance data of the Fore-Loaded turbine blade and that of conventional turbine blade. In consequence, this two dimensional Fore-Loaded turbine blade expected to reduce the number of blades by 23%

FIRST TRIAL TEST TURBINE

To confirm the three dimensional high load characteristics of the Fore-Loaded turbine blade, a single stage test turbine was designed and manufactured in JFY1999-2000. As the first trial test turbine, the Fore –Loaded turbine blade was applied to only nozzle vanes of the test turbine. Aerodynamic tests on the first trial test turbine were conducted in JFY2001.

BASIC DESIGN

The basic specification of the first trial test turbine was shown in Table. 1. It was determined, taking account of the efforts of the research and development project of supersonic transport propulsion system (HYPR). The stage loading factor standing for output per a turbine stage was set to approximately 2.0, and the total-to-total efficiency was set to 90%. The trend of efficiency to turbine stage loading factors is shown in Fig. 1. The specification of the first trial turbine was on the standard level in 2000. In addition, the velocity triangle of the first trial turbine is shown in Fig. 2.

Table.1 Test turbine specification

		Second trial	First trial	(Ref.only) Base line turbine
Stage Loading Factor		2.00	2.01	2.00
Efficiency		90%	90%	90%
Stage Reaction		0.82	0.75	-
Reduction of the number of blades	Nozzle	-28%	-28%	-
	Blade	-27%	-7%	-

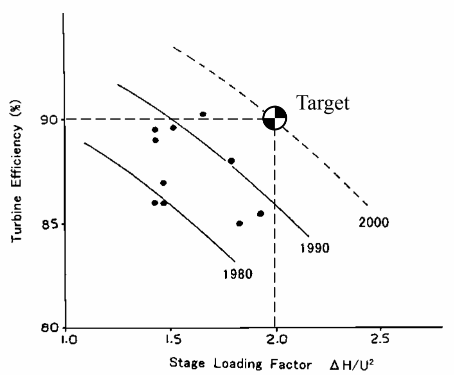


Fig. 1 The trend of turbine efficiency to stage loading factor

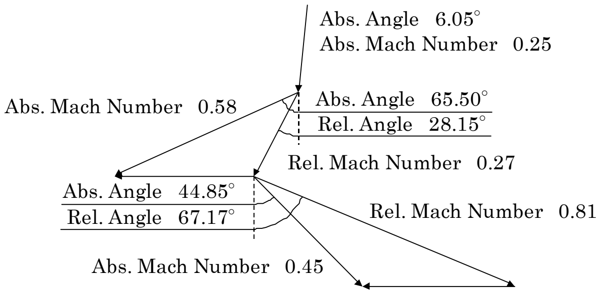
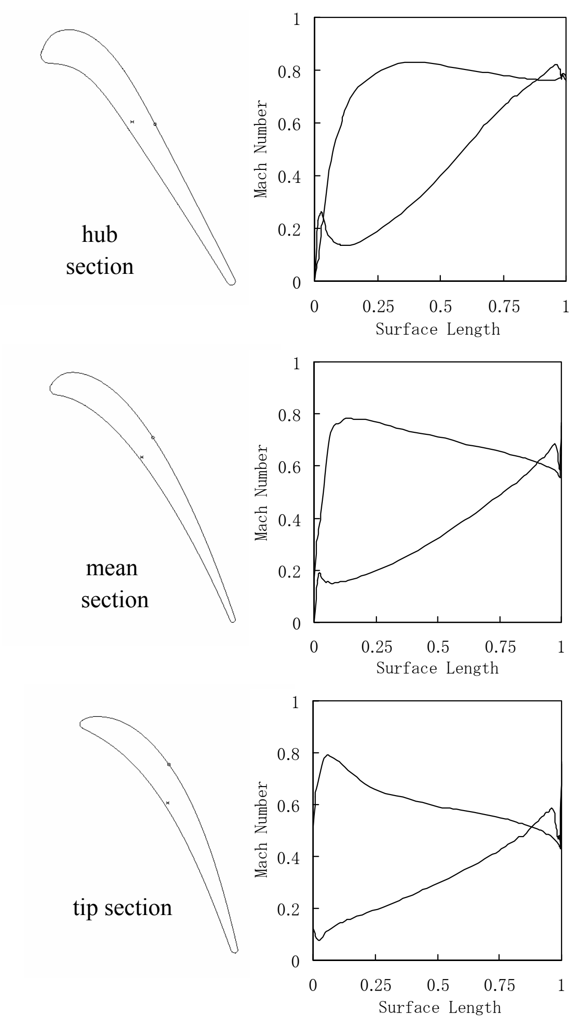


Fig.2 Velocity triangle of first trial test turbine (on the mean section plane)

The Fore-Loaded turbine blade was applied to nozzle vanes, and resulted in 28% decrease in the number of nozzle vanes. As the first trial turbine, conventional rotor blades were selected, because the influence of the flow field of the Fore-Loaded turbine nozzle vanes on that of the rotor blade installed behind the nozzle vane row was unknown. But the number of rotor blades was 7% smaller than the base line turbine because it was decided to avoid resonance with nozzle vanes or other structures.



(Blade Profile) (Mach number distribution on blade surface)

Fig.3 The nozzle vane of the first trial turbine

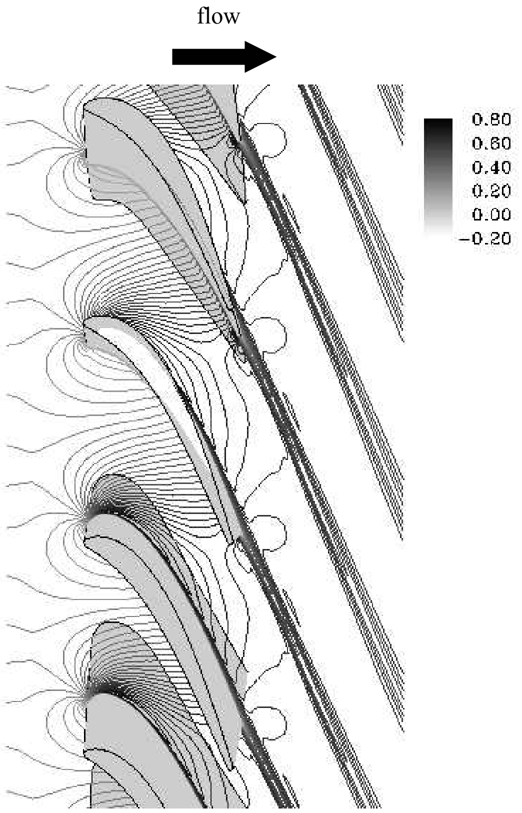


Fig.4 Mach number contours on the mean section in the first trial nozzle vane passage (3D viscous analysis)

DETAILED AERODYNAMIC DESIGN

Axisymmetrical flows were calculated based on findings from the basic design, so as to define the three dimensional flow patterns.

Based on this three dimensional flow pattern design, the three dimensional nozzle vane profile with the Fore-Loaded velocity distribution was designed. Fig. 3 shows cross sectional views of the three basic planes (hub, mean, and tip), and Mach number distributions on the blade surface at the basic planes obtained from the three dimensional viscous flow analysis. In addition, Fig. 4 shows the Mach number contours in the mean flow passage of the nozzle vane.

A conventional three dimensional blade profile was selected as the first trial test rotor blade. This rotor blade was analyzed by the three dimensional viscous flow analysis.

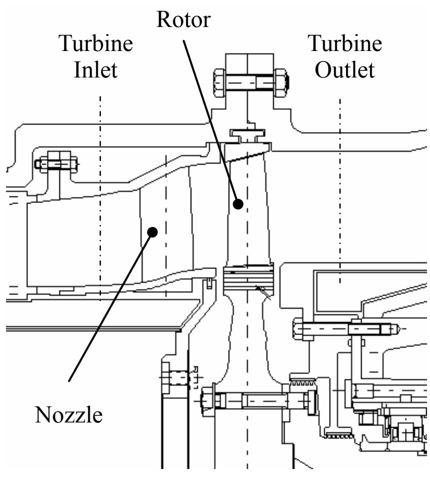


Fig.5 Aerodynamic test equipment

As a result, both the three dimensional nozzle vane with the Fore-Loaded velocity distribution and the conventional rotor blade were successfully designed. Hub-tip ratios of the first trial nozzle vane and rotor blade were 1.45 and 1.46, respectively. And aspect ratios of them were 1.23 and 1.80.

AERODYNAMIC TEST

Fig. 5 shows a cross section of the aerodynamic test equipment. At two axial locations upstream and downstream of the test turbine stage, spanwise distributions of total and static pressure, total temperature and flow angle were measured by five hole pitot probes traversed tangentially and thermometers. These measurements were used to estimate the aerodynamic performance

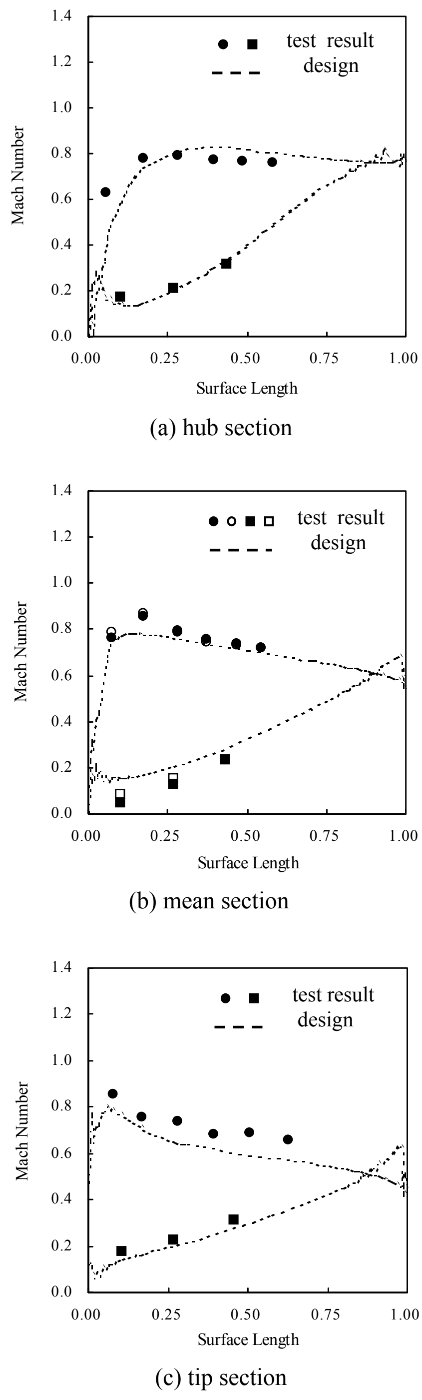


Fig.6 Mach number distribution on blade surface of the first trial nozzle vane

of the first trial turbine stage.

In addition, for the 4 nozzle vanes, 6 static pressure holes on the suction surface and 3 holes on the pressure surface in the chordwise location on the three basic planes (hub, mean, and tip) were drilled. The diameter of the static pressure holes was 0.5mm. These measurements were used to calculate Mach number distributions on the three basic planes.

TEST RESULT AND DISCUSSION

Fig. 6 shows the experimental results of the Mach number distributions on the three basic planes of the nozzle vanes with Fore-Loaded velocity distribution. In addition, it shows the numerical results of the Mach number distributions from three dimensional viscous analysis of the nozzle vane. The comparison showed acceptable agreement between experimental and numerical results.

However, the total-to-total efficiency of the first trial turbine was 88.1%, 2% short in target efficiency. Total-to-total efficiency was calculated using the equation; Eq.(1).

$$\eta = \frac{h_{in} - h_{out}}{h_{in} - h_{iso}} \qquad (1)$$

where

η : Total-to-total Efficiency
h_{in} : Specific enthalpy at nozzle inlet
h_{out} : Specific enthalpy at rotor outlet
h_{iso} : Isentropic specific enthalpy at rotor outlet

Fig. 7 shows the spanwise total-to-total efficiency distribution. The efficiency at radial location from hub to about 70% span from the hub was almost similar to that of design. Therefore, it shows that the Fore-Loaded turbine blade was able to be applied to the tested nozzle vane without losing aerodynamic performance of the turbine stage.

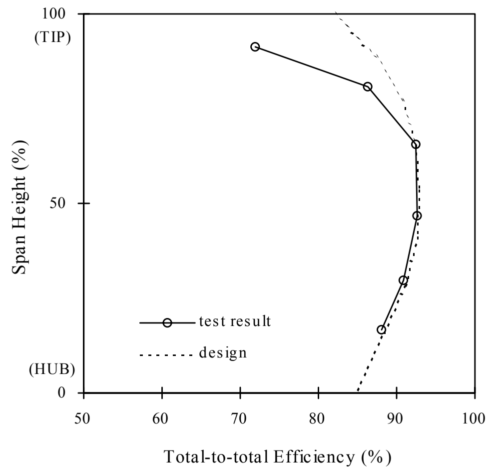


Fig.7 Spanwise efficiency distribution of the first trial turbine

While, in the tip region, the efficiency was about 10% short in that of design. Because we weren't able to calculate the efficiency of each blade row (nozzle vane and rotor blade) separately from the test result, the reason of low efficiency in the tip region was assumed by the comparison of test results of the flow fields with numerical predictions.

Fig.6(c) shows that unacceptable flows weren't found in Mach number distribution on the tip plane of the nozzle vane.

Accordingly, the three dimensional viscous analysis with tip clearance of the rotor blade was conducted. Fig. 8 shows the exit flow angle distribution from the re-analysis. It confirms that tip clearance flow made an unacceptable effect on the total performance of the first trial turbine.

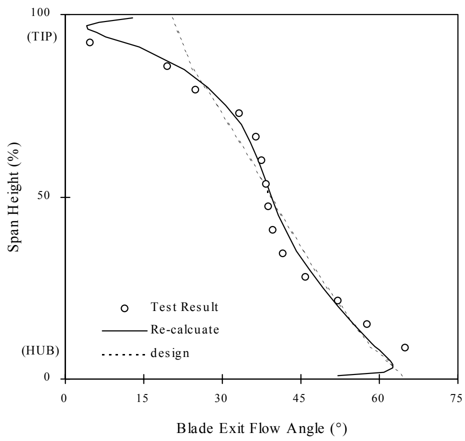


Fig.8 Rotor exit flow angle from the re-analysis with tip clearance

As a result, the serious reason of low efficiency in the tip region was assumed that the flow field in the tip region of the rotor blade was unacceptable. In other words, the first trial turbine where the Fore-Loaded turbine blade is applied to the nozzle vane will perform the target aerodynamic performance by modifying the flow field in tip region of the rotor blade.

SECOND TRIAL TEST TURBINE

Based on the assessment of the performance data of the first trial turbine, the second trial turbine was designed in JFY 2002. The Fore-Loaded turbine blade was applied to also rotor blade of the test turbine. The same nozzle vane tested in the first trial turbine was used for the second trial. Aerodynamic tests on the second trial turbine will be conducted in JFY 2003.

BASIC DESIGN

The basic specification of the second trial turbine was shown in Table.1. The stage loading factor and the total-to-total efficiency of the second trial turbine was similar to those of first trial turbine. In addition, the same nozzle vane of the first trial turbine was used for the second trial turbine.

The tip endwall profile of the second trial turbine was changed to modify the flow fields inside the rotor passage near the tip region. The Fore-Loaded turbine blade was applied to the rotor blade of second trial turbine, and resulted in 27% decrease in the number of rotor blades. The velocity triangle of the second trial turbine is shown in Fig. 9

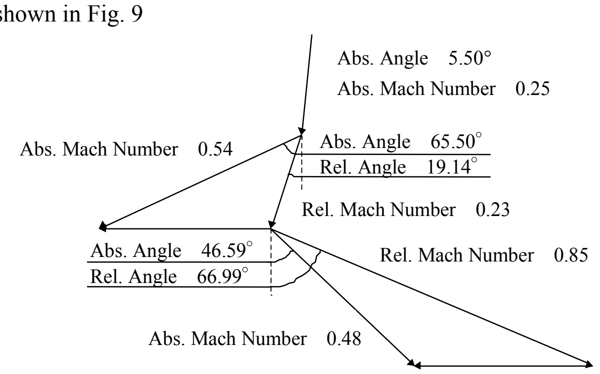
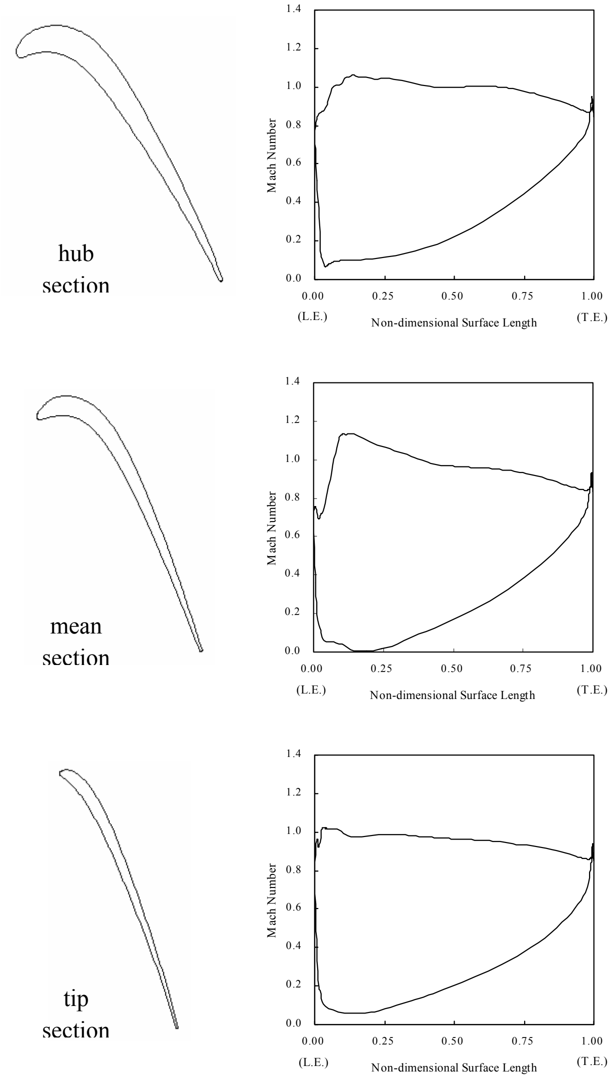


Fig.9 Velocity triangle of second trial test turbine (on the mean section plane)

DETAILED AERODYNAMIC DESIGN

The three dimensional rotor blade profile with the Fore-Loaded



(Blade Profile)

(Mach number distribution on blade surface)

Fig.10 The rotor blade of the second trial turbine

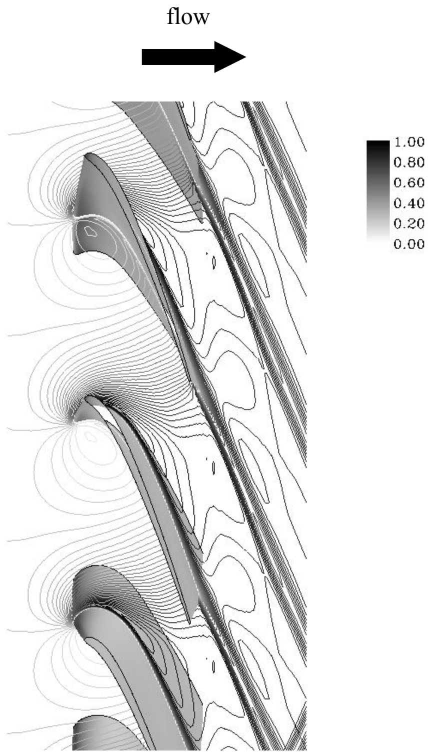


Fig.11 Mach number contours on the mean section in the second trial rotor blade passage (3D viscous analysis)

velocity distribution was designed. Fig. 10 shows cross sectional profiles of the three basic planes (hub, mean, and tip), and Mach number distributions on the blade surface at the basic three planes obtained from the three dimensional viscous flow analysis. In addition, Fig. 11 shows the Mach number contours in the mean flow passage of the rotor blade. As a result, the three dimensional rotor blade with the Fore-Loaded velocity distribution was successfully designed. Hub-tip ratio of the second trial rotor blade was 1.46, and aspect ratio of it was 1.53.

Furthermore, to confirm the overall performance of the second trial turbine, the three dimensional viscous stage flow analysis of the second trial turbine stage was conducted. Fig. 12 shows that the

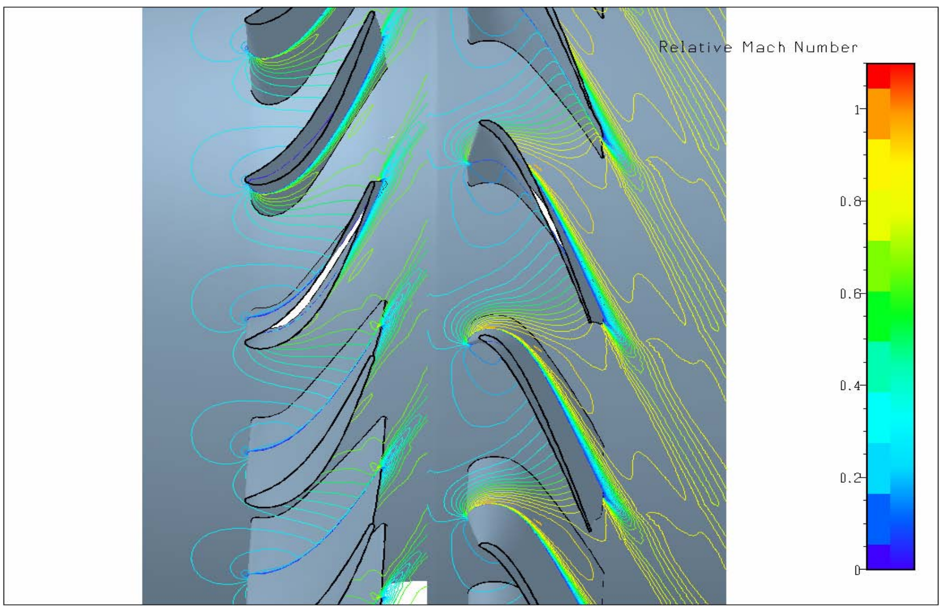


Fig.12 Mach number contours on the mean section in the second trial turbine stage (3-D stage flow analysis)

Mach number contours in the mean flow passage of the second trial turbine stage from the stage flow analysis. As a result, no unacceptable flow field was found. Therefore the second trial turbine was expected to perform the target aerodynamic performance.

Aerodynamic tests on the second trial turbine will be conducted in JFY2003.

CONCLUSION

This paper described the development status of the Fore-Loaded turbine blade. A single stage test turbine was designed to confirm the three dimensional high load characteristics of the Fore-Loaded turbine blade. The stage loading factor standing for output per a turbine stage was set to approximately 2.0, and its total-to-total efficiency was set to 90%. The specification of test turbine is similar to standard level in 2000.

At first, the Fore-Loaded turbine blade was applied to the nozzle vanes of the first trial test turbine. The first trial turbine will perform the target aerodynamic performance by modifying the flow field in tip region of the rotor blade.

Furthermore, the Fore-Loaded turbine blade was applied to also rotor blade of the second trial turbine. The same nozzle vane tested in first trial turbine was used for the second trial test turbine. Consequently, the number of nozzle vanes with a conventional blade profile was reduced by 28%, and the number of rotor blades with a conventional blade profile was reduced by 27%.

Aerodynamic tests on the second trial turbine will be conducted in JFY2003.

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