DEVELOPMENT OF A TRANSONIC LINEAR COMPRESSOR CASCADE TEST FACILITY

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ABSTRACT

A new transonic cascade wind tunnel has been designed and built to investigate compressor blade aerodynamic characteristics. This is a continuous open-loop type facility capable of operating at subsonic and transonic Mach numbers. Air is supplied by a 4-stage centrifugal compressor and temperature is controlled by a separate cooling system. Reynolds number can be varied in the range of 1.0-2.0×10^6 and relative humidity 5-80%. The facility has a 120 mm by 140 mm cross sectional area test section. The cascade is composed of 5 blades. There are two bypass passages in the lower and upper parts of the cascade. There is also a transonic wall which prevents shock reflection via bleeding system. To minimize 3D effects from the sidewalls there is a sidewall boundary layer bleeding system upstream of the cascade. The cascade is designed with relatively high aspect ratio of 2.4. The preliminary compressor cascade experiment have been conducted in case Mach number of 0.81. Experimental results show periodic inlet flow (Pressure coefficient standard deviation 0.01), shock images, and good agreement of blade loading with CFD predictions.

NOMENCLATURE

AVDR	Axial Velocity Density Ratio $\left(=\frac{\rho_2 V_{ax,2}}{\rho_1 V_{ax,2}}\right)$
c	blade chord length
Cp	loading coefficient $\left(=\frac{P-P_{s,1}}{P_{t,1}-P_{s,1}}\right)$
H	blade span
i	incidence angle
L	nozzle length, (=470.5 mm)
Ma	Mach number
P	pressure
Re	Reynolds number $\left(=\frac{\rho V c}{\mu}\right)$
s	pitch
t	axial location
T	temperature
V	velocity
x	chordwise location
y	pitch wise location
γ	specific heat ratio
α	flow angle
β	blade angle
δ	deviation angle
μ	air dynamic viscosity
ρ	air density
ω	loss coefficient $\left(=\frac{P_{t,1}-P_{t,2}}{P_{t,1}-P_{s,1}}\right)$
Ø	diameter

Subscripts

1	cascade inlet
2	cascade outlet
ax	axial
s	static
ss	Suction surface
ps	pressure surface
t	total

INTRODUCTION

Modern compressors are characterized by high pressure ratios, high efficiency, and low weight. To meet those requirements, the tip region of compressor blades encounters transonic flow. The transonic compressor flow fields are complex including shock waves, mixed subsonic and supersonic flow regions, and shock boundary layer interactions. Due to these complexities, both understanding of compressor flow field and validation of computational / theoretical code with experimental results are essential.

Linear cascade device is an attractive experimental method for the analysis of flow field and code validation due to its cost-effectiveness, easy access for instrumentation, and the ability to vary aerodynamic parameters independently. In linear cascade testing, flow periodicity from passage to passage is important. Therefore, many researchers stressed the importance of periodicity and suggested various methods. In 1993, Starken et al [1] gave a detailed discussion on cascade testing facility and instrumentation, covering the issue of flow periodicity for subsonic and transonic conditions. Gostelow [2] suggested removing sidewall boundary layers, and Davis [3] reported shock cancellation with porous wall which helps to make periodic flow. In 1992, Steinert [4] suggested an inlet flow angle determination method without disturbing the transonic inlet flow. Those methods and techniques have been adopted in the new transonic cascade test facility.

In transonic compressor cascade experiments, downstream pressure of cascade have to be pressurized via throttle system to make cascade flow un-started. In AGARD paper [5], two types of tailboard & throttle system are introduced. One is of transonic cascade device of DLR, the mechanism of long tailboard with throttle device at the end of the tailboard is used. The other is of supersonic cascade device of ONERA, the mechanism of short tailboard followed by a free shear layer is used.

The present paper describes a new transonic compressor cascade test facility and its preliminary experimental results.

EXPERIMENTAL FACILITY

Wind Tunnel Facility. The two-dimensional transonic linear cascade wind tunnel, shown in Fig. 1, is an open-loop, continuous type facility. Air is supplied at up to 10 bar by a 4-stage centrifugal compressor. Total pressure is reduced by a pressure regulator valve to 5 bar, and there is another control valve for fine control of total pressure after the regulator valve. Total temperature can be controlled via coolers which are located between compressor stages. Thus total pressure and total temperature can be individually controlled, and independent control of Reynolds number and relative humidity is possible. Cascade inlet Mach number is controlled by a throttle valve which is located downstream of the cascade for subsonic flow and by changing the nozzle for supersonic flow. Operating conditions are summarized in Table 1.

Table 1. Operating Condition

Total Pressure	150 - 400 kPa
Total Temperature	300 – 380 K
Reynolds number	1 - 2x10^6
Relative humidity	5 – 80%
Mach Number	0.3 – 1.4

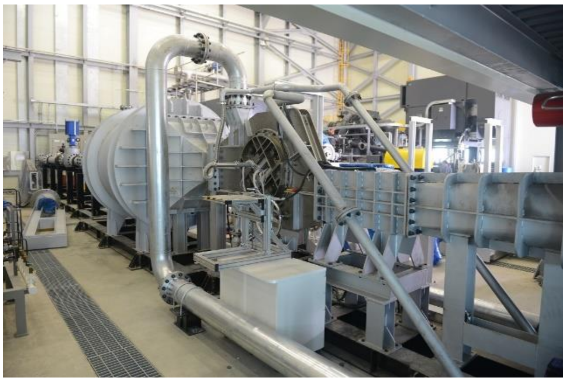

Figure 1. Transonic Cascade Wind Tunnel

Test Section. The test section, shown in Fig. 2, is 120 mm X 140 mm dimension with 5 blades. These blades are mounted on the turntable, so that incidence angle can be changed from -7 to +7 degrees. There is a sidewall boundary layer bleeding system [6] to minimize the sidewall boundary layer upstream of the cascade, and bleeding rate is controlled by a valve. For operation in the transonic and supersonic range, the upper wall of the test section is porous and equipped with a bleeding system, which is called a transonic wall [7]. This transonic wall enables a continuous transition from subsonic to supersonic flow, and even stable test condition at inlet Mach number of 1.0. It also help to make the flow periodic by minimizing the shock reflection from the ceiling. There are two bypass passages on the upper and lower parts of the cascade. These passages are divided from main flow and controlled via separate control valve to facilitate periodic flow.

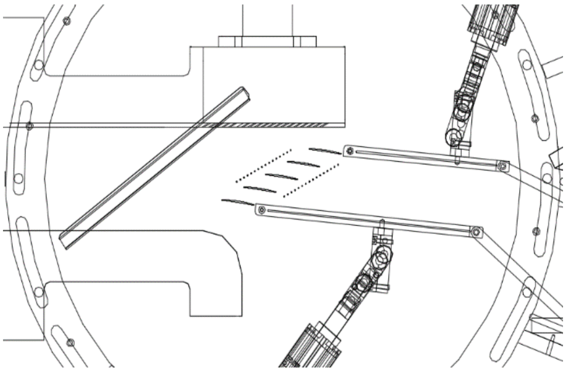

Figure 2. Schematic of Test Section

Cascade. Cascade is composed of 5 blades of a transonic compressor. Its design aspect ratio is 2.4 to minimize the sidewall effects, and blades are supported by sidewalls made of plexiglass which enables optical access to the cascade and adoption of Schlieren technique (see Fig. 3). Cascade parameters are summarized in Table 2.

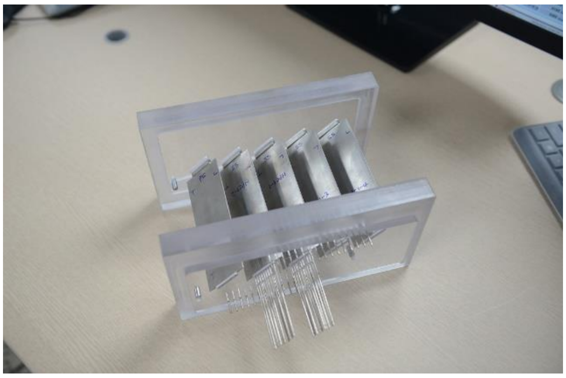

Figure 3. Compressor Cascade Model

Table 2. Cascade Parameter

Number of blades	5
Chord length(c)	50 mm
Aspect ratio(H/s)	2.4
Solidity(c/s)	1.326
Stagger angle	144.5°

INSTRUMENTATION

Measurement methods. Measurement variables are summarized in Table 3, and measurement methods are as follows. Periodicity of inlet and outlet flow is checked via 16 static taps (Ø 0.5 mm) which are located t/c= -0.3 (upstream) and t/c= 0.2 (downstream) of cascade, respectively. These static taps cover the 2nd ~ 4th passages to check the periodicity of vicinity flow of the target passage which is 3rd passage. The inlet Mach number is calculated by the total pressure in the settling chamber which is measured with a Kiel probe (product of AEROPROBE, tip diameter 4.76 mm, E-type thermocouple), and static pressure which is measured by averaging pressures of the 16 static holes which are located 0.3c upstream of the cascade. Following Steinert's method [4], incidence angle is calculated by comparing the blade loading of the leading edge region of suction surface with CFD results. Blade loading is measured with 10 static taps (Ø 0.3 mm) which are distributed on the suction surface of the 3rd blade and pressure surface of the 4th blade. Downstream flow is measured with a 3-hole probe (product of AEROPROBE, bent type, tip diameter 1.6 mm), at the 0.2c downstream of the cascade. To conduct shock visualization, Schlieren technique (Xenon lamp, 200mm parabolic window, 1/2" CCD camera, 1290X960 pixel) has been adopted.

Table 3. Measurement Variables

Inlet Mach number, Ma	$\sqrt{5\left[\left(\frac{P_{t,1}}{\sum P_{s,1}}\right)^{\frac{\gamma-1}{\gamma}}-1\right]}$
Incidence angle, i	$\alpha_1-\beta_1$
Loading coefficient, Cp	$\frac{P-P_{s,1}}{P_{t,1}-P_{s,1}}$
Loss coefficient, ω	$\frac{P_{t,1}-P_{t,2}}{P_{t,1}-P_{s,1}}$
Deviation angle, δ	$\alpha_2-\beta_2$

Sensors. As this facility was designed for steady flow measurement, Netscanner PSI 9116 16-channel sensor (accuracy of 0.05% of full scale: 0.1 kPa / 206 kPa) is adopted for pressure measurements for the Kiel probe, 3-hole probe, and static taps. For temperature measurement, E-type thermocouple is used which is shielded in Kiel probe. To measure relative humidity in the settling chamber, HMT331 (product of VAISLA, accuracy of 1%) sensor is adopted.

Uncertainty. Calculated uncertainties of measurement variables using above instrumentation and measurement techniques are summarized in Table 4.

Table 4. Uncertainty of Measurement Variables

Inlet Mach number, Ma	± 0.5%
Incidence angle, i	± 0.5°
Loading coefficient, Cp	± 1.5%
Loss coefficient, ω	± 3%
Deviation angle, δ	± 0.5°

PRELIMINARY EXPERIMENTAL RESULTS: TRANSONIC COMPRESSOR CASCADE

Test setup. Transonic compressor cascade experiments have been conducted for inlet Mach numbers of 0.81 and incidence angle of +4°.

Experimental results (Ma=0.81, i=+4°) Experimental results of Mach number 0.81 is shown from Fig. 4 to 6, and the results are summarized in Table 6. From Fig. 4 to 5, inlet flow looks quite periodic. Blade loading distribution shows good agreement with CFD results in Fig. 6.

Table 6. Comparison of Cascade Aerodynamic Characteristic Variables

Variable	EXP	CFD
Loss coefficient	0.028	0.031

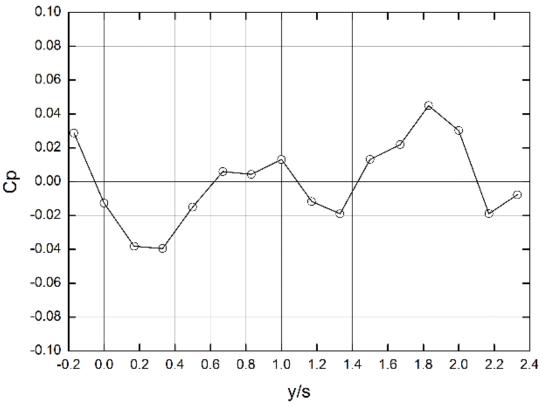

Figure 4. Upstream Periodicity (Ma=0.81)

Figure 5. Shock Visualization (Ma=0.81)

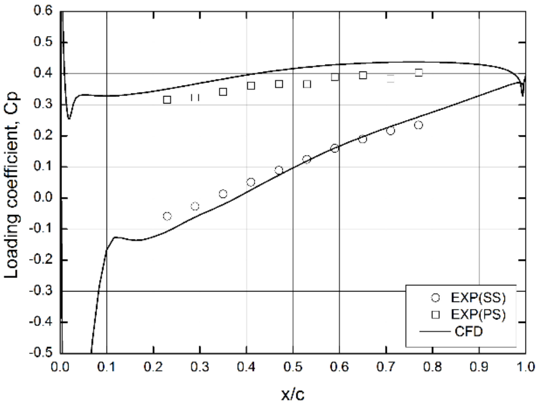

Figure 6. Blade Loading (Ma=0.81)

SUMMARY

A new transonic cascade wind tunnel has been designed and built to investigate compressor blade aerodynamic characteristics. It is a continuous open-loop type test facility and separate control of total pressure and total temperature is possible. The operating range of this transonic cascade wind tunnel is 150 -400 kPa of total pressure, 300 - 380 K of total temperature and 5 – 80% of relative humidity. Cascade is composed of 5 blades which are mounted on the turntable. So the incidence angle can be changed by rotating the turntable from -7° to +7°. There are two bleeding systems, one for sidewall boundary layer removal and the other for preventing shock reflection from the ceiling. Two bypass passages which are located in the upper and the lower part of the cascade help to make periodic flow.

Preliminary experiments have been conducted. In the compressor cascade experiment, it shows quite periodic flow, and good agreements of blade loading distribution and loss coefficient with CFD results.

ACKNOWLEDGMENTS

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REFERENCES

[1] Starken, H., Fottner, L., 1993, Sieverding, C.H., Schreiber, H.A., Steinert, W., Hoorelbeke, M.M., Gaillard and Losfeld, ‘Linear cascades’, Chapter 2, Advanced Methods for Cascade Testing, AGARD-AG-328.

[2] Gostelow, J.P., 1984, “Cascade Aerodynamics”, Pergamon Press, New York.

[3] Davis J.W., 1973, ‘Optimization of wave cancellation in variable porosity transonic wind tunnel flows’, NASA TN D-7432

[4] Steinert, W., 1992, Fuchs, R. and Starken, H. ‘Inlet Flow Angle Determination of Transonic Compressor Cascades,’ Journal of Turbomachinery, Vol. 114, pp. 487-493.

[5] Charles Hirsch, 1993, ‘Advanced Methods for Cascade Testing’, AGARD-AG-328

[6] A. Fage, F.R.S., 1944, ‘Design of Suction Slots’, Aeronautical research council reports and memoranda.

[7] James L. G., 1984, ‘Transonic wind tunnel wall interference minimization’, AIAA