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Visualization of Transient Three-dimensional Flow Field with Rotating Stall in a Diagonal Flow Fan

Shiomi, N.*, Cai, W. X.*, Kaneko, K.* and Setoguchi, T.*

* Department of Mechanical Engineering, Saga University, 1 Honjo-machi, Saga 840-8502, Japan.

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***Abstract*:** An Unsteady flow field with rotating stall cells in a high specific-speed diagonal flow fan has been investigated experimentally. Although a general feature of stall cells has already indicated, i.e., the number of stall cells is one and its propagating speed is approximately 80 percent of rotor speed, little has been known about the flow field when a rotating stall occurs because of its unsteadiness. In order to capture the behavior of the rotating stall cell, measurements of the flow field at the rotor inlet were carried out with a single slant hot-wire. Those data were processed by a so-called "double phase-locked averaging" (DPLA) technique, which enabled to capture the flow field of the cell in the reference co-ordinate system fixed to the rotor. As a result, time-dependent ensemble averages of the three-dimensional velocity components at the rotor inlet have been obtained and the behavior of the rotating stall cell has been illustrated with each velocity component.

***Keywords*:** turbomachinery, rotating stall cell, unsteady flow, DPLA technique, fan.

1. Introduction

A diagonal flow fan has relatively high efficiency, low noise level and wide operating range. However when its specific-speed becomes high, its pressure-flow rate curve tends to indicate an unstable characteristic with a positive gradient in low flow range similar to axial flow fan. It is well known that the rotating stall is the main cause to this unstable characteristic, and the flow field with rotating stall cells indicates remarkable unsteadiness due to a partly reversed flow. For axial turbomachines many researchers (Moore and Greitzer, 1986; Poensgen and Gallus, 1996; Saxer-Felice et al., 1998) have investigated the flow field with rotating stall cells. However, there are very few studies on unsteady flow fields in the diagonal flow fan in the past. Recently, Kaneko et al. tried to measure the unsteady flow field in a rotating stall region by use of a hot-wire and pressure probe. Although from a series of studies by Kaneko et al. (1993, 1995, 1997) unsteady flow characteristics of the rotating stall cell were clarified to some extent, little has been known about the behavior of the stall cell.

Most of surveys for the internal flow field of turbomachines have been carried out using a phase-locked averaging method, because the flow field changes periodically with blade passing frequency. However when the flow field includes a rotating stall cell, the stall cell propagates at different speed with rotor blade. Therefore it is impossible to clarify the behavior of the stall cell by means of the ordinary phase-locked averaging method. In order to capture the behavior of the stall cell, a so-called "double phase-locked averaging" (DPLA) technique was developed by Kuroumaru et al. (1999) and Inoue et al. (2000). In this method it is assumed that propagating speed of the stall cell is constant.

In this study, the authors carried out an experimental investigation on the unsteady flow field with the rotating stall in a high specific-speed diagonal flow fan at Saga University. At the rotor inlet velocity measurements were performed with a hot-wire anemometer by use of a single slant hot-wire probe. Those measured data were processed by DPLA technique and the unsteady flow field with the rotating stall cell was illustrated for time-dependent ensemble averages of the three-dimensional velocity component. And the behavior of the stall cell was clarified with each velocity component.

2. Experimental Apparatus and Procedure

2.1 Test Rig and Instrumentation

The schematic layout of the test section of a high specific-speed research diagonal flow fan is shown in Fig. 1. It consists of a rotor with 310-mm-dia at the tip of blade leading edge, 347-mm-dia at the tip of blade trailing edge and stator with 380-mm-dia and hub/tip ratio of 0.6. The rotor comprises 6 blades designed by use of a quasi-three-dimensional method based on the two-dimensional cascade data. The rotor was manufactured precisely by NC milling machine to secure the geometry of the blade. The stator comprises 11 blades. Selection of its blade element was carried out using two-dimensional cascade data of circular-arc blade. This diagonal flow fan stage has the flow rate coefficient of $\phi = 0.345$, and the pressure coefficient of $\psi = 0.250$ at the design point. Specific speed of the test fan is approximately 1600 (rpm, m^3/min, m). Although this is a relatively high value for a diagonal flow fan, this value was chosen to compare the flow field with an axial compressor, for which the researches on unsteady flow in the rotating stall region have been actively done. The blade tip clearance is 0.5 mm (0.45 percent of blade height at leading edge) for the rotor.

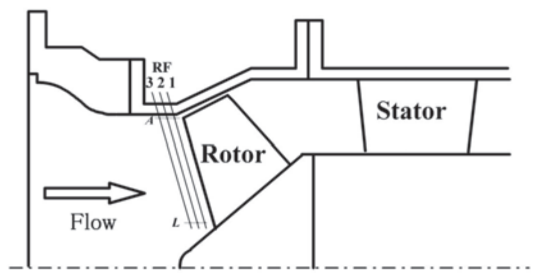

Fig. 1. Schematic layout of test fan.

Table 1. Specifications of test fan, rotor and stator.

Test fan			Rotor	Stator
Total pressure coefficient	$\psi = 0.250$	Blade section	NACA65	Circular-arc
Flow coefficient	$\phi = 0.345$	Number of blade	6	11
Specific speed	$n_s = 1620$	Mean solidity	0.88	1.30
Angle of casing	20 [deg.]	Mean aspect ratio	0.79	0.67
Angle of hub	40 [deg.]	Vortex design	Free vortex	Free vortex
Hub/tip ratio (at stator)	0.6			

The stage performance was evaluated for a combination of this rotor and stator. The total pressure rise of the stage was obtained from the pressure difference between the inlet and outlet chamber by subtracting the aerodynamic loss of the other element. The flow rate was measured by a flow nozzle connecting with outlet chamber.

Flow surveys were carried out in the inlet cross sections to the rotor by using a single slant hot-wire. The three probe traverse lines RF1, RF2 and RF3 are shown in Fig. 1, where the distances between the rotor blade leading edge and each traverse line are 5 mm (RF1), 10 mm (RF2) and 15 mm (RF3), respectively. Spanwise measurement stations are 12 points on each measurement line. The hot-wire probe was rotated about its axis at interval of 36 deg for 10 orientations of the sensor.

2.2 Double Phase-locked Averaging Technique

In order to clarify the transient behavior of the stall cell, a so-called "double phase-locked averaging" (DPLA) technique was utilized. By use of DPLA technique the data were synchronously acquired with both rotor and the cell rotation. To utilize DPLA technique, two trigger signals are necessary. One is from the rotor blade signal and the other is from the stall cell signal. The rotor blade signal is obtained from encoder mounted on the rotor shaft.

The rotating stall cell signal is taken by setting a threshold level for the low-pass filter (50 Hz) signal of the pressure transducer in which the blade passing frequency has been removed. The pressure transducer (Entran EPE-58) used in this measurement has 80 kHz natural frequency and 2 psi pressure range.

The data acquisition is made upstream of the rotor by hot-wire survey whose data sampling frequency is 20 kHz. Therefore, at each location the sensor signals for approximately 387 circumferential sampling points per one rotor rotation are acquired and approximately 65 data sampling points are included in one blade pitch.

The location of the stall cell relative to a blade is determined as follows. At first, the reference point of the cell called rotating stall reference point (RS_{ref}) is taken at a point where the rotating stall cell signal crosses its average value from negative to positive as illustrated in Fig. 2(b). The interval between one RS_{ref} point and next point corresponds to a period of traveling stall cell. Secondly, a blade pitch is divided into 10 windows as shown in Fig. 2(d). These windows are called trigger point (TP) in this paper. Thirdly, to which TP each RS_{ref} point belongs is checked. For example, in Fig. 2 RS_{ref} (i–1) point belongs to TP = 0.4 and the raw data between RS_{ref} (i–1) and RS_{ref} (i) are labeled as "TP = 0.4". At last, all data that belong to the same TP are averaged at each sampling point.

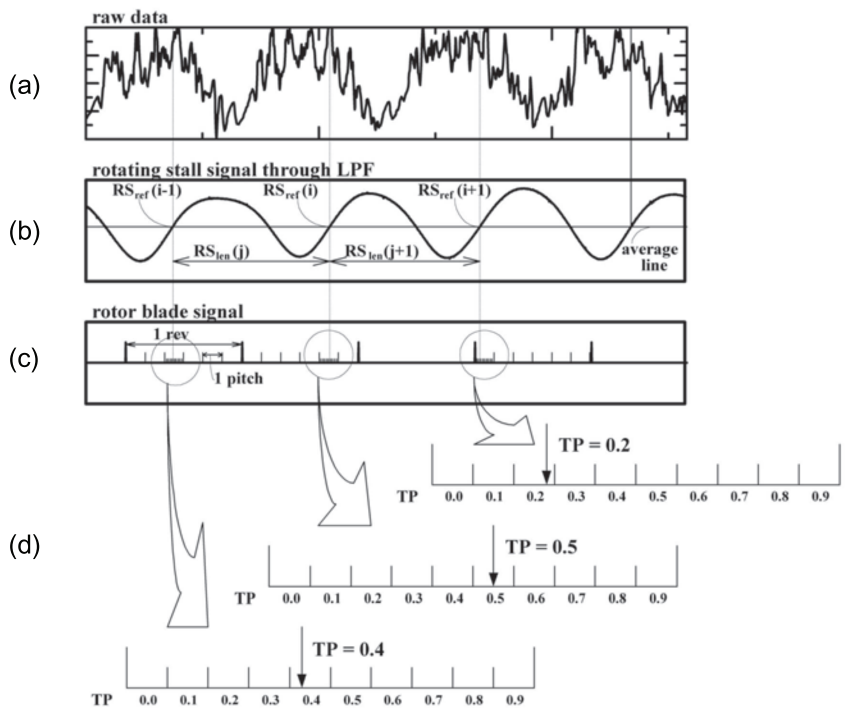

Fig. 2. Outline of DPLA technique.

It is assumed that the propagating speed of the stall cell is constant. Indeed, the frequency of the rotating stall, which was checked by using the FFT analyzer when the surveys were performed, was not constant exactly. It was approximately 39 Hz and with fluctuations less than 0.5 Hz. Therefore, the variance of data measured on the propagating speed of the stall cell was less than 1.25 percent.

3. Results and Discussion

3.1 Overall Characteristics of Test Fan

The performance characteristics of the test fan are shown in Fig. 3, where the ordinate represents flow rate (ϕ) and the abscissa indicates total pressure coefficient (ψ), efficiency (η) and torque coefficient (τ). When flow rate is reduced from the design point (DP in Fig. 3), sharp drop in pressure coefficient occurs near ϕ = 0.200. It was explained by Kaneko et al. (1993, 1995, 1997) that this sharp drop in pressure coefficient was due to occurrence of a rotating stall with one-cell and its propagating speed was approximately 80 percent of rotor speed. In order to clarify the behavior of stall cell, internal flow measurements were conducted at this rotating stall condition (ϕ = 0.195).

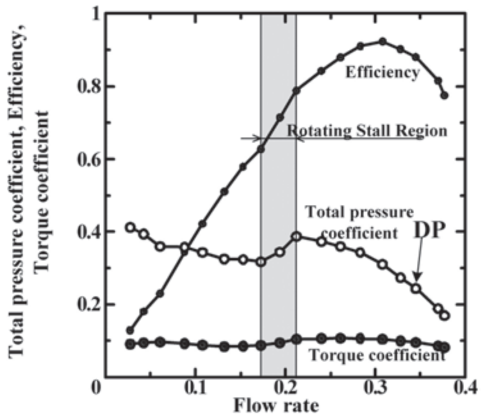

Fig. 3. Characteristic curves of test fan.

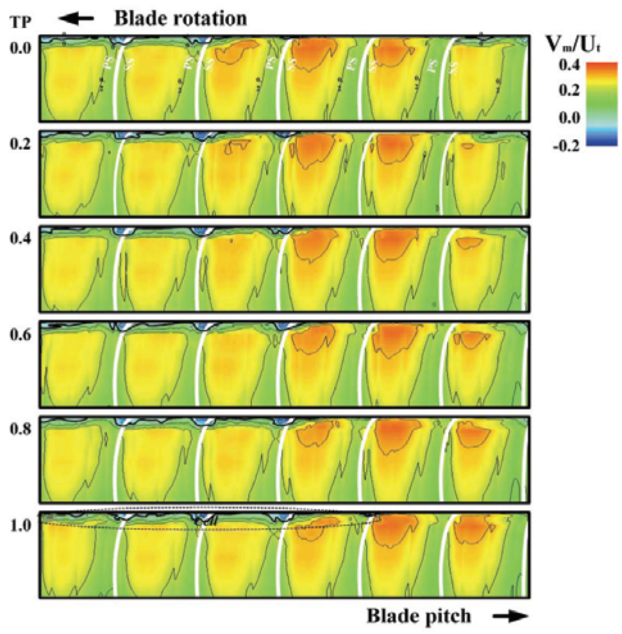

Fig. 4. Meridional velocity distributions at RF1 (full span pictures).

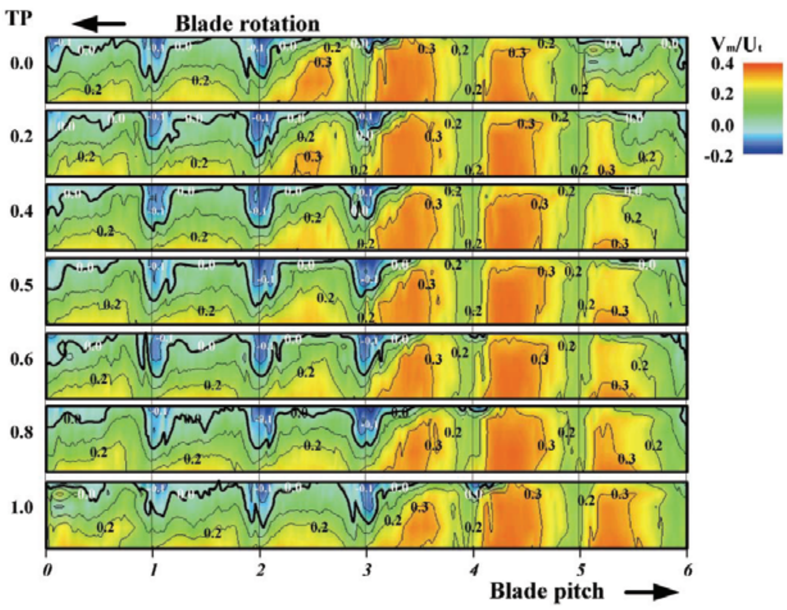

Fig. 5. Meridional velocity distributions at RF1 (near blade tip 80 percent span).

3.2 Meridional Velocity (V_m) Distributions at RF1

Figures 4 and 5 show the contour maps of meridional velocity (V_m) at RF1 under the rotating stall condition with propagating TP. Figure 4 shows the full span pictures and Figure 5 shows the part span pictures near the blade tip. In all these figures, abscissa and ordinate indicate spanwise direction and blade pitches, respectively. TP indicates the location of the stall cell relative to a blade, and the rotating stall cell moves 1 pitch of the blade row from TP = 0.0 to 1.0. The red region indicates high value of V_m and the blue region low value or reversed flow. In this case, the blue regions correspond to the stall cell. The meridional velocity is normalized by rotor rotating speed at blade tip and its maximum value is about 0.4. The blade rotating direction is shown at the top of the figure.

It is observed in Fig. 4 that the blue region is limited near tip. Hence the cell in this fan is part-span cell. It is also seen that the cell is moving from left to right in these figures with progressing TP. The relative propagating direction is opposite to the rotor blade motion. In this paper, hereafter, the right side edge of the cell is defined as the cell leading edge and the left side as the cell trailing edge. Although the stall cell is moving at constant speed as a whole, the local speeds of both edges are not constant. It seemed that at the cell trailing edge the reversed flow region is gradually moving but at the cell leading edge it is suddenly jumping into next blade (see in Fig. 5, from TP = 0.5 to 0.6). This means that the circumferential size of the cell is not constant and it changes periodically when propagating. It is also observed that strong reversed flow exists near the blade pressure surface (PS) at the blade tip. On the other hand, it is found that high meridional velocity regions exist out of the cell near the blade tip.

3.3 Tangential Velocity (V_θ) Distributions at RF1

Figure 6 shows the contour maps of tangential velocity (V_θ). In this figure, abscissa and ordinate indicate spanwise direction and blade pitches, respectively. The red region indicate high value and the blue regions low. In this case, the high value regions correspond to reversed flow region in Fig. 4 or Fig. 5, i.e., these are stall cell regions. The tangential velocity is normalized by rotor tip speed U_t and its maximum value is approximately 0.8. This value is very high and it is about two times of V_m. The blade rotating direction is shown at the top of the figure.

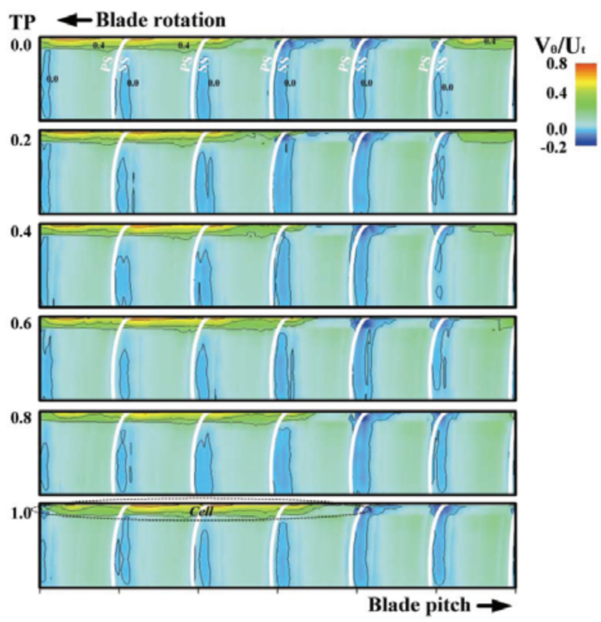

Fig. 6. Tangential velocity distributions at RF1 (full span pictures).

In these figures the stall cell region is shown more clearly than the V_m distributions (Figs. 4 and 5). From these figures it is observed that very high V_θ regions are near the blade suction surface (SS) at the blade tip and it extends toward the mid blade pitch. It means that when the separation occurs on the blade SS the separated region is moving with the blade. Outside the cell the low velocity regions exist periodically. These indicate the effect of blade potential on the flow field. For the movement of the stall cell, although it is seen that the cell leading edge is suddenly jumping into the next blade in V_m pictures, it is observed that the cell leading edge is gradually moving in V_θ pictures.

3.4 Spanwise Velocity (V_n) Distributions at RF1

Figure 7 shows the contour maps of spanwise velocity (V_n). The spanwise velocity is normalized by rotor tip speed (U_t) and its maximum value is approximately 0.15. As this value is lower than V_m and V_θ, it seems that the effect of spanwise velocity on the flow field is not so large. The blade rotating direction is shown at the top of the figure. It is noted that the direction of spanwise velocity is parallel to the probe axis, as shown in Fig. 1. Therefore when the flow comes in parallel to the casing wall, its value becomes minus, on the other hand, parallel to the hub its value is plus.

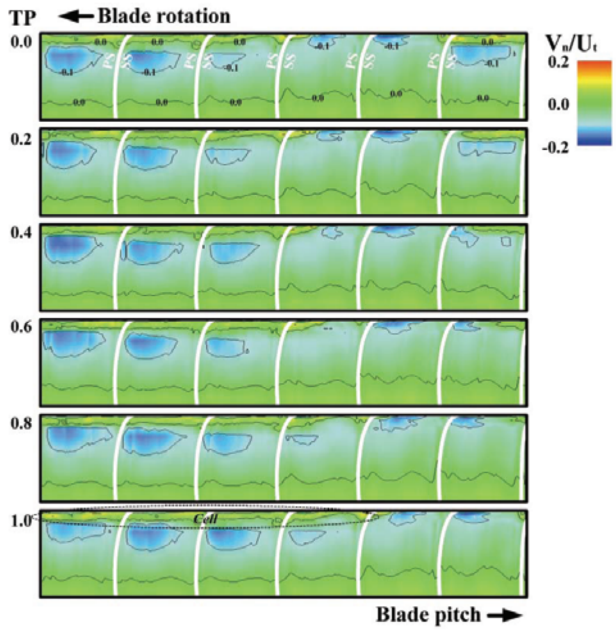

Fig. 7. Spanwise velocity distributions at RF1 (full span pictures).

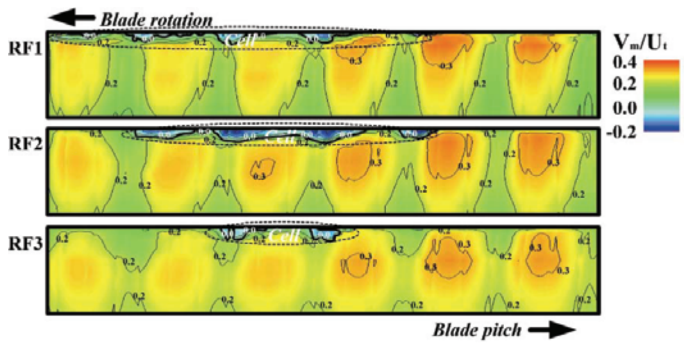

Fig. 8. Comparison of meridional velocity distributions at three planes (TP = 1.0).

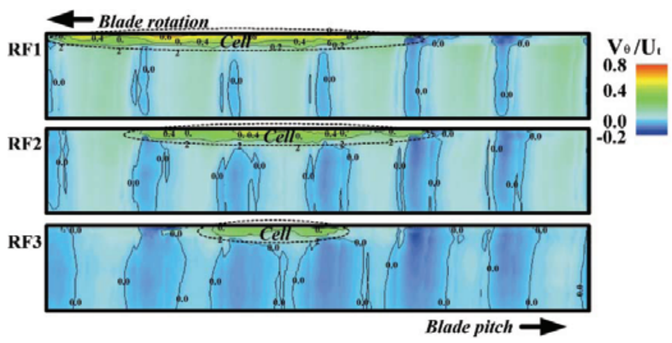

Fig. 9. Comparison of tangential velocity distributions at three planes (TP = 1.0).

At the clean flow region (out of the cell) near the blade tip, the V_n value shows minus, but as stated above, this means that the inlet flow of this region is parallel to the outer casing. Also, near the hub, the V_n value shows plus, then the flow is parallel to the hub. Inside the cell, its value is mainly plus except for very near tip regions. This means that inside the cell the flow is mainly outwards.

3.5 Comparison of Velocity Fields at Different Measurement Planes

Figures 8 and 9 show the contour maps of meridional and tangential velocity distributions for three measurement planes (RF1, RF2 and RF3) at TP = 1.0, respectively. The top figure is for RF1, the middle is for RF2 and the bottom is for RF3 plane. For the color, the red is high and the blue low. These values are normalized by rotor tip speed U_t. The blade rotating direction is shown at the top of the figure.

It is observed that the circumferential size of the cell becomes rapidly small with upstream distance, but its radial size dose not change. It is also observed that the strength of the reversed flow is almost the same for each measurement plane, but that the value of V_θ is rapidly weakened. Generally the effect of the stall cell on the rotor inlet flow field is weakened, as its distance becomes far from the plane of the rotor leading edge.

4. Conclusion

The unsteady flow fields at the rotor inlet with the rotating stall cell in a high specific-speed diagonal flow fan were visualized experimentally. To get these pictures, the measurements with a single slant hot-wire probe were conducted and these data were processed by use of DPLA technique. The main conclusions are obtained as follows.

1. Strong reversed flow regions exist at the blade PS near the outer casing inside the cell. On the other hand, the sound main flow regions exist out of the cell.
2. High tangential velocity regions exist at blade SS near the outer casing inside the cell.
3. The flow is mainly outwards inside the cell.
4. The effect of the cell on the rotor inlet flow field is weakened, as its distance becomes far from the rotor leading edge.

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Author profile

Norimasa Shiomi: He received his master degree in Mechanical Engineering from Saga University in 1996. After that he has been working in Mechanical Engineering Depertment, Saga University as assistant. His research interest is turbomachinery, especially diagonal flow fan.

Wen Xin Cai: He received his BS (Eng) degree in Fluid Engineering from Department of Power Engineering, Huazhong University of Science and Technology (HUST, China) in 1990 and his master degree in Fluid Enineering from Xi'an Jiaotong University (China) in 1993. He received Ph.D (Eng) from Department of Mechanical Engineering, Saga University (Japan) in 2001. Now he is interested in the research on flow in fan.

Kenji Kaneko: He received Ph.D in Mechanical Engineering from Kyushu University in 1969. After completion of his Ph.D he has been a faculty member of Mechanical Engineering Department, Saga University, and currently is a professor. His research fields are fluid engineering and turbomachinery, especially internal flow of turbomachinery.

Toshiaki Setoguchi: He received Ph.D in Mechanical Engineering from Kyushu University in 1981. After completion of his Ph.D program, he has been a faculty member of Mechanical Engineering Depertment, Saga University, and currently is a professor. His research interests include compressible flows and turbomachinery, especially turbines for wave energy conversion.