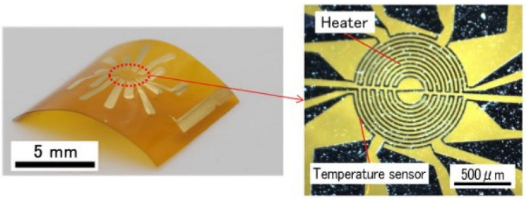
Development of Flow Angle Measurement Technology on Casing Surface of Compressor Blade Using Thin Sensor



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In order to improve the efficiency and reliability of fluid machinery, such as gas turbines and pumps, the control and suppression of secondary flow and separation inside fluid machinery is important. Fluid machinery faces a challenge in reducing losses caused by the flow through gaps at the tip of rotor blades. However, probe measurement in a narrow gap disturbs the flow field, so the measurement is difficult. Therefore, Mitsubishi Heavy Industries, Ltd. (MHI) has developed a thin flow angle measurement sensor in collaboration with the Tokyo University of Science, which can be applied to very narrow gaps while minimizing interference with the flow. The sensor was applied to an axial-flow compressor test machine to verify if it can measure flow angles. This report describes the outline of the developed thin flow angle measurement sensor and the axial flow compressor test results.

1. Introduction

Increasing the efficiency and reliability of fluid machinery is important not only to reduce fuel costs, but also to reduce carbon dioxide emissions. To this end, the control and suppression of secondary flow and separation inside fluid machinery is an issue, and it is necessary to understand the flow field, including not only the main flow but also the leakage flow between the stator and rotor blades. For example, since the behavior of blade tip leakage flow in axial flow compressors affects performance degradation and surge margins, there is a need to understand the phenomenon by measuring the flow angle in the narrow gap at the tip of the rotor blade (blade tip gap) and to monitor the flow angle. In general, the flow angle and velocity field in blade tip gaps were measured conventionally by visualization inspection using oil flow on the casing surface, PIV, etc., because the flow field is affected if a measurement probe is inserted. However, this method has disadvantages such as the inability to measure changes one by one caused by changes in operating conditions, contamination of the flow path by particles and oil, and a limited measurement area due to the necessary installation of an optical window, light source, and camera. Against this background, we have developed a thin flow angle measurement sensor using the Micro Electro-Mechanical Systems (MEMS) technology in collaboration with the Tokyo University of Science in order to realize real-time measurement without the need to install optical windows, etc., while minimizing the influence on the flow [(1)].

This report presents an overview of the developed flow angle sensor and the results of installing it on the casing surface of an axial flow compressor to measure the flow angle variation with changes in operating conditions.

2. Configuration and principle of flow angle measurement sensor

2.1 Configuration of sensor

Figure 1 shows the configuration and specifications of the thin flow angle measurement sensor. The sensor consists of a circular heater in the center and six 55-degree-spanning temperature sensing elements with 5-degree intervals around the heater. The sensing element area is as small as 1.08 mm in diameter (heater area: 1 mm in diameter), and the sensor is as thin as several tens of micrometers. The sensor film is made of polyimide film, which is flexible and has

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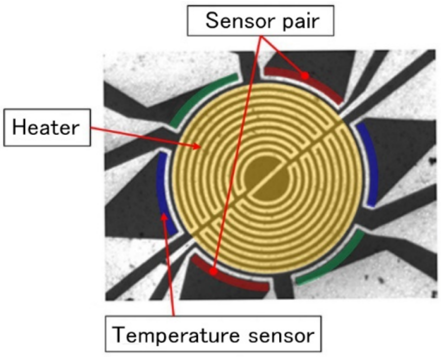
excellent mechanical properties, the electrodes are made of gold, and the adhesive layer is made of chromium. Because of its thinness and flexibility, the sensor can be installed on curved surfaces with little interference to the flow field, even in narrow gaps. Furthermore, its small size allows multiple sensors to be placed in a limited space, which can improve spatial resolution.



Number of sensor pairs		3
Sensor spanning angle		55°
Substrate		Polyimide
Electrode		Cr–Au
Thickness	Au: Electrode	100nm
	Cr: Adhesive layer	10nm
	Polyimide: Substrate	25μm

Figure 1 Configuration and specifications of thin flow angle measurement sensor

2.2 Measurement principle

Flow angle measurement is based on the same principle as that of a hot wire flow meter: with the central heater kept at a constant temperature higher than the ambient temperature by PID control, the temperature difference between opposing temperature sensors (a sensor pair) is converted into a resistance value difference and then extracted by a bridge circuit. **Figure 2** shows a conceptual diagram of the flow angle measurement principle. Since the gas around the heater is always heated, the temperature field changes when a flow occurs, causing a bias in the temperature distribution around the heater along the air flow direction. The bias in the temperature distribution is measured by three temperature sensor pairs. By fitting the relationship between the circumferential positions of the temperature sensor pairs and the measured values with a trigonometric function, the flow angle is calculated.

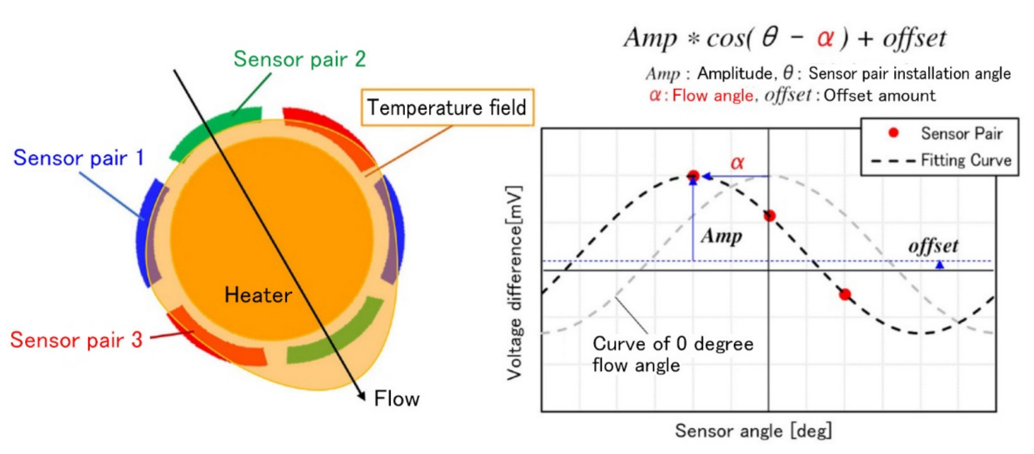


Figure 2 Principle of flow angle measurement

3. Characteristics of flow angle measurement sensor

To check the characteristics of the flow angle measurement sensor, we conducted a flow angle calibration test. **Figure 3** shows the calibration test wind tunnel used. The test wind tunnel has a channel 10 mm high, 100 mm wide, and 600 mm long. The sensor is installed on the wall 500 mm downstream from the inlet nozzle, so that the turbulent flow is well developed at the sensor position. The sensor mounting part can be rotated to any angle. The test was conducted while changing the relative angles between the sensor and the mainstream to obtain angular characteristics. The Mach number was varied in the range of 0.1 to 0.5, and the heater temperature was kept 50°C higher than the ambient temperature by PID control.

Figure 4 shows the measurement results. The horizontal axis in the figure represents the actual flow angle, and the vertical axis represents the flow angle measured by the developed thin sensor. The measurement accuracy error is less than 10 degrees except for 0 degrees, confirming that the flow angle measurement is possible in the subsonic velocity range. The error is considered to be mainly due to manufacturing defects in the sensor. We plan to reduce the error by optimizing the manufacturing process, including electrode design, and by introducing an amplifier in the bridge circuit.

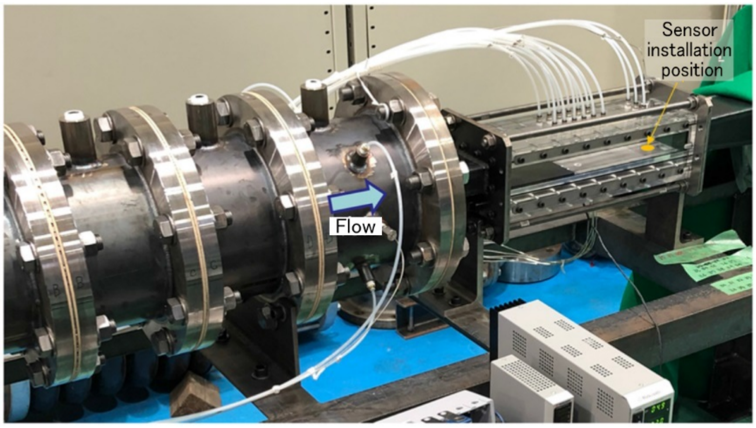


Figure 3 Appearance of calibration test wind tunnel

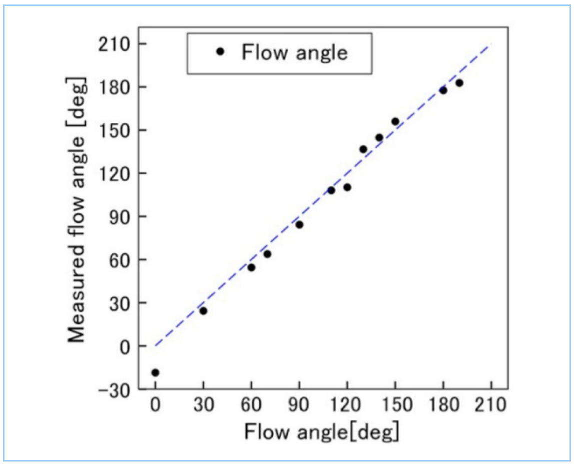


Figure 4 Flow angle measurement calibration test result

4. Axial flow compressor test

4.1 Test equipment

The axial flow compressor test was conducted using our 1.5-stage rig test equipment as shown in **Figure 5**. The rated speed was 5,500 rpm, the planned pressure ratio was 1.08, and the rotor blade clearance was approximately 3.4% of the blade height. To install the sensor on the casing, which is a cylindrical surface, a flexible sheet including sensor wiring was utilized. As shown in **Figure 6**, the flexible sheet with four flow angle measurement sensors in the axial direction was installed on the casing surface of the first-stage rotor blade to measure the flow angle. The flow angle measurement sensors were placed at one point in front of the first-stage rotor blade and three points in the first-stage rotor blade passing area. The flexible sheet was attached to a special mounting plate and assembled into the inner casing, taking care not to create any steps from the flow surface. The flexible sheet contains sensor wiring, but its flexibility allows it to be bent several times in a narrow space to allow wiring to be pulled outward. The wiring is connected to various measurement substrates outside the test equipment, connecting the sheet to a measurement PC for data acquisition.

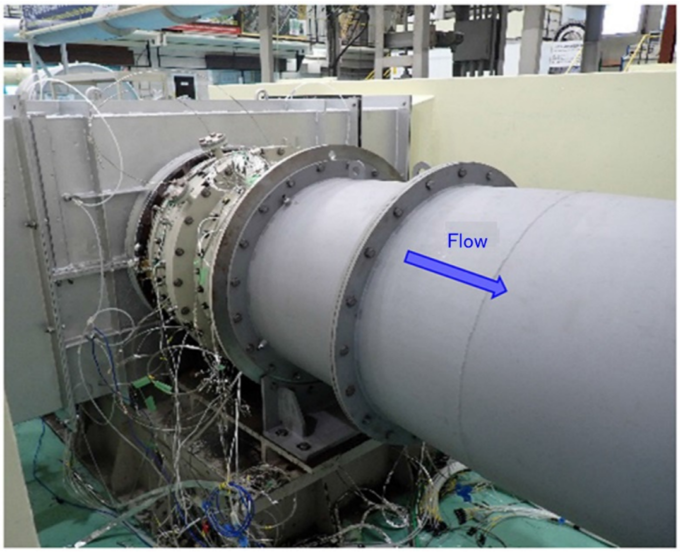


Figure 5　Axial flow compressor rig test equipment

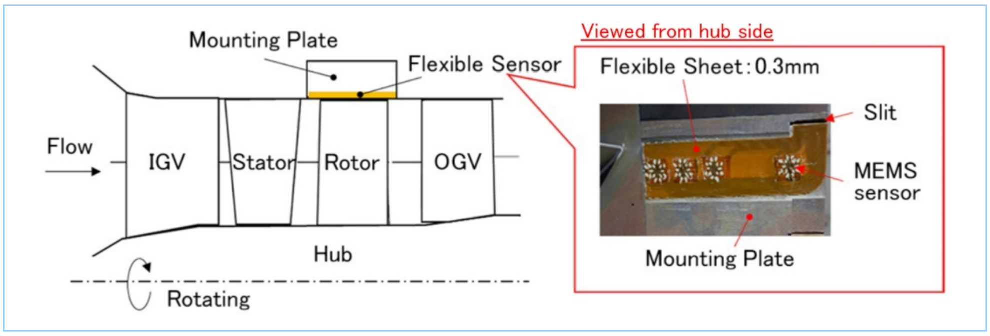
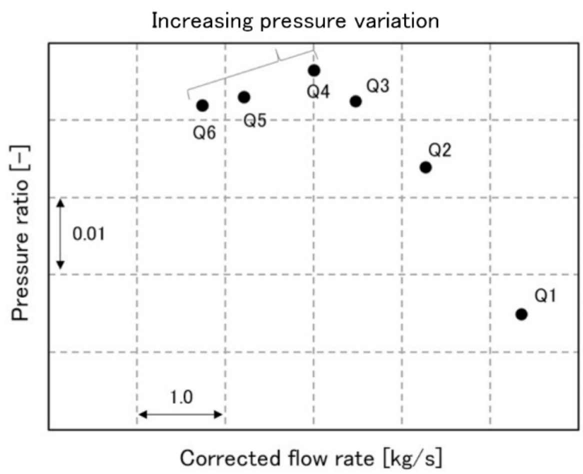


Figure 6　Measurement points and sensor layout

4.2　Test conditions

As shown in **Figure 7**, the test was conducted at six operating points. At the three points (Q1 to Q3) including the design operating point (Q1), which are plotted as a downward slope on the graph, the flow angle changes mainly due to the operating point changes were measured for comparison with the numerical analysis results. At the three points (Q4 to Q6), which are plotted as an upward slope on the graph, the test was conducted mainly to confirm the integrity of the sensors because of the large first-stage rotor blade pressure variation and the highly unsteady operating range there. Since one sensor was found to be damaged during installation in the test equipment, only three points in the axial direction were evaluated as the measurement results. For the other sensors, it was confirmed that the sensor signals could be measured at all operating points, including Q4 to Q6, without any interruption during the test.



Symbol	Purpose	Condition
Q1	Comparison of flow angle variation between measurement and CFD	Design point
Q2		Intermediate point
Q3		High pressure ratio
Q4	Confirmation of sensor integrity	Maximum pressure ratio
Q5		Upward slope (1)
Q6		Upward slope (2)

Figure 7　Test conditions

5. Flow angle measurement result

5.1 Numerical analysis method

We modeled one blade row from the intake duct to the exhaust section of the rig test equipment on which the test was conducted and performed a numerical analysis to simulate the test conditions. In the numerical analysis, a structured multi-block RANS solver in-house code was used and the Spalart-Allmaras model was employed as the turbulence model for steady-state analysis. The analytical grid was created entirely on a structured grid, with approximately 20 million cells in total. The inlet boundary conditions were given as total pressure and total temperature, and the outlet boundary condition was given as static pressure, which was adjusted to match the pressure ratio during the test.

5.2 Comparison with measurement result

Figure 8 compares the operating points between the test and analytical results. The analytical result is shown as a dashed line, and the same points as the test pressure ratios are plotted. The result from the design point (Q1) to the point (Q3) before the peak of the pressure ratio show that the result generally simulated the test conditions despite a slight deviation in the corrected flow rate only for Q3. Next, **Figure 9** compares the absolute flow angles between the measurement and analysis results for the operating points Q1 to Q3. The horizontal axis represents the axial position, and the vertical axis represents the absolute flow angle. The measured values are time-averaged values, which are equivalent to the averaged circumferential flow variation with rotor blade rotation. Error bars indicate the standard deviation from the time-averaged value. The analytical result is circumferential averages at the same axial positions, which represent the average flow.

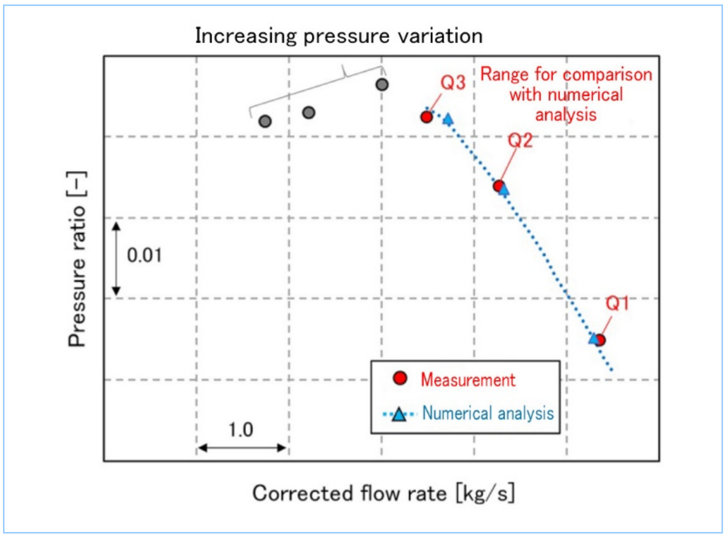


Figure 8 Comparison of test operating point and numerical analysis result

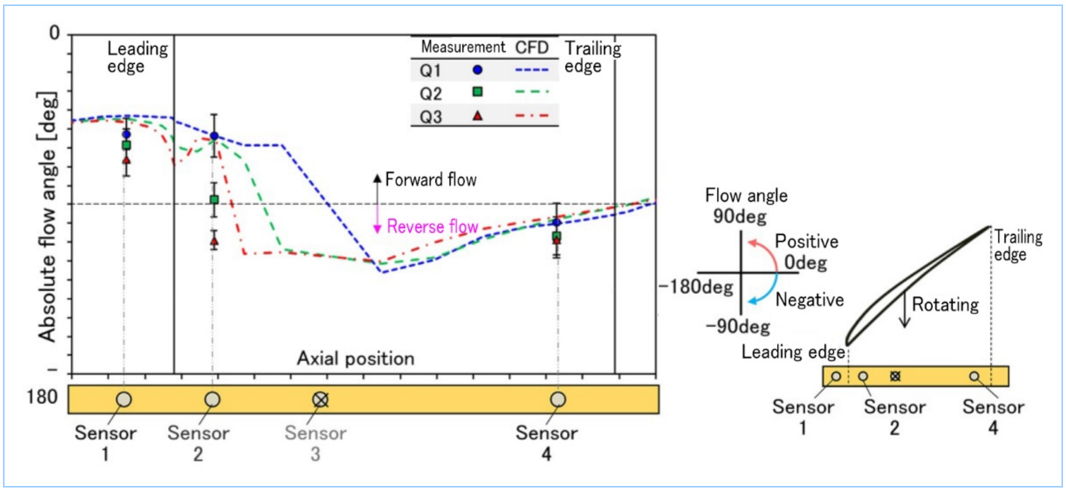


Figure 9 Comparison of flow angle between measurement and numerical analysis results

At the operating point Q1, the design point, the measurement and analysis results are in good agreement overall, confirming that this sensor can measure the flow angle at the end face of the casing in the rotor blade gap. Furthermore, even at the downstream-most measurement position (Sensor 4), which is in the reverse flow area, the measurement and analysis results are in good agreement, indicating that this sensor can measure the flow angle even in the reverse flow area and can be used to determine the reverse flow. On the other hand, the deviation between the measured and analyzed values increases at the operating points (Q2 and Q3), which are on the higher-pressure ratio side than Q1, and the deviation is particularly large at the downstream measurement position (Sensor 2) of the leading edge (L.E.) of the first-stage rotor blade. **Figure 10** shows the critical flow lines on the rotor blade casing surface obtained from the analysis. The area near Sensor 2, where forward and reverse flow are mixed in the circumferential direction on the high-pressure ratio side due to blade tip leakage vortices and the flow varies greatly in the circumferential direction, is considered to be affected by the lack of time response of the sensor and the predictive accuracy of the analysis. In the future, we plan to further improve the accuracy of the sensor by verifying its time response and making comparisons with the results of non-steady-state analysis.

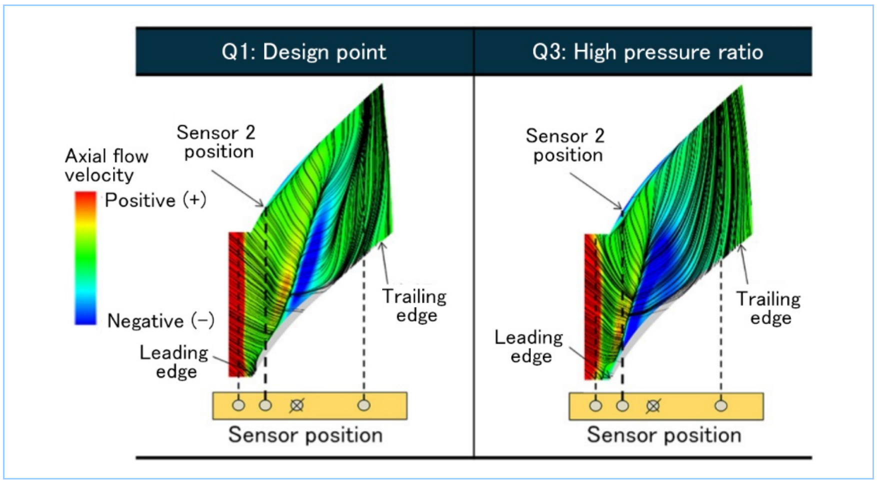


Figure 10　Comparison of critical flow line on rotor blade casing surface

6. Conclusion

MHI has developed a thin flow angle sensor in collaboration with the Tokyo University of Science, which can be applied to narrow gaps where it was conventionally difficult to measure flow angles, in order to improve efficiency and reliability of fluid machinery. We applied the developed thin flow angle sensor to the casing surface of the tip of the rotor blade of an axial flow compressor and confirmed that it can measure the flow angle at the design point and can also be used to determine the reverse flow area. In addition, by applying multiple sensors to blade tips and seals of fluid machinery, it is possible to capture changes in flow angle due to clearance expansion caused by repetitive start-up and shutdown, etc., and to identify the position of a stage where clearance expansion occurs before overhauling, which is expected to contribute to performance recovery proposals. Moving forward, we plan to optimize the manufacturing process, including electrode design, and verify the time response of the sensor in order to improve measurement accuracy and productivity, and also improve the sensor according to needs in order to apply it to a wider range of fluid machinery.

References

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(2) Naoto Omura et. al, Flow angle measurement on the casing surface of the compressor blade tip using a flexible MEMS sensor, 100th Annual Meeting of Fluids Engineering Division in Japan Society of Mechanical Engineers, OS07-04