Journal of Visualization, Vol. 5, No. 3 (2002) 255-261

Flow Measurement in a Transonic Centrifugal Impeller Using a PIV

Hayami, H.*1, Hojo, M.*2 and Aramaki, S.*1

*1 Institute of Advanced Material Study, Kyushu University, Kasuga, Fukuoka 816-8580, Japan.
*2 Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka 816-8580, Japan.

Received 25 November 2001.
Revised 9 March 2002.

***Abstract*:** Laser velocimetries, such as LDV or laser-2-focus (L2F) velocimetry, have been widely used for a flow measurement in a high-speed rotating impeller. A particle image velocimetry (PIV) is one of the popular velocity measurement techniques for the ability to measure a velocity field. And a PIV offers an extensive velocity field in an extremely shorter measurement time than the laser velocimetries. In the present experiment, a PIV was applied to a flow measurement in a transonic centrifugal impeller. A phase locked measurement technique every 20% blade pitch was performed to obtain a velocity field over one blade pitch of the inducer. The measured velocity field at the inducer of impeller clearly showed a shock wave generated on the suction surface of a blade. The validity of the present technique was also discussed.

***Keywords*:** centrifugal compressor, centrifugal impeller, particle image velocimetry, transonic flow, shock wave.

1. Introduction

In a single-stage high-pressure-ratio centrifugal compressor, the relative velocity to the impeller usually exceeds the velocity of sound. That is, a generation of a shock wave is unavoidable, and it also affects the compressor performance. To improve the performance of a transonic centrifugal compressor, the velocity field near the inducer has been measured using a laser-2-focus (L2F) velocimetry (Hayami et al., 1985; Hayami, 1998).

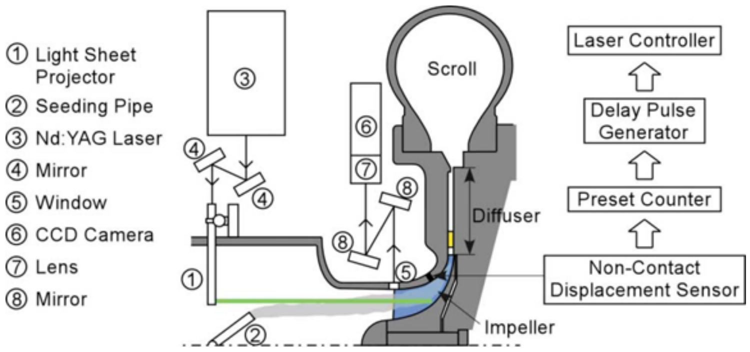
Particle image velocimetries (PIVs) have major features of both laser velocimetries and optical visualization techniques. And they are very attractive owing to the feasibility of simultaneous and multipoint measurement. PIVs offer an extensive velocity field in an extremely shorter measurement time than laser velocimetries. Unlike laser velocimetries, a PIV needs the light sheet illumination. Thus, the application of a PIV has one problem that a light sheet projector must be inserted into a flow, although laser velocimetries enabled non-contact measurements. Some researchers applied PIVs to the case of high-speed rotating turbomachinery, such as a blade-to-blade rotor passage in a subsonic axial compressor (Tisserant and Breugelmans, 1997), and a flow with a passage shock wave in a transonic axial compressor (Wernet, 2000).

In the present paper, a velocity field in the inducer of a transonic centrifugal impeller was measured using a PIV. To obtain a velocity field over one blade pitch, a phase locked measurement technique was used, and then the validity of the measurement was discussed. The velocity vector field and a shock wave in the inducer are presented and discussed.

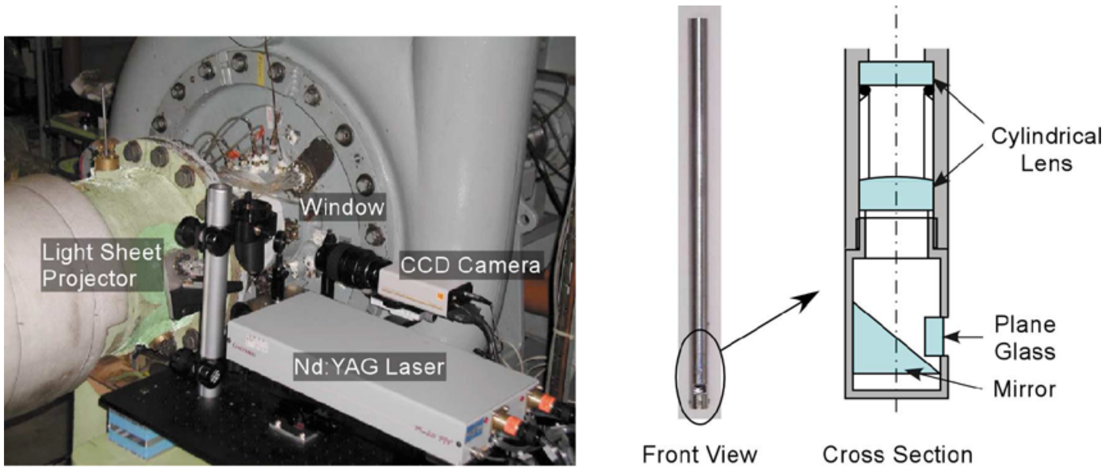
2. Experimental Apparatus and Procedure

2.1 Transonic Centrifugal Compressor

A transonic centrifugal compressor was tested in a closed loop with HFC134a gas. The meridional profile of the test compressor is shown in Fig. 1(a). The open shroud impeller had 15 main blades and 15 splitter blades with a backward sweep angle of 40 deg at the exit. The impeller diameter was 280 mm, and the inducer tip diameter and the hub diameter were 172 mm and 80 mm respectively. Downstream of the impeller was a diffuser consisted of a low-solidity cascade with eleven vanes and two parallel walls 9.4 mm apart from each other (Hayami, 1998).



(a) meridional profile of the test compressor and PIV system



(b) PIV system and compressor

(c) light sheet projector

Fig. 1. Experimental apparatus.

2.2 PIV System

Figures 1(a) and (b) show the PIV system based on a double-frame PIV technique with a double-pulsed Nd:YAG laser (Continuum Minilite II) with 25 mJ/pulse. A pulsed laser beam was reflected by two mirrors, and then passed through a light sheet projector of 10 mm in outer diameter and 200 mm long. It was located at 370 mm upstream from inducer leading edges. And it has a traverse unit to set at any inducer radius. The projector consists of two cylindrical lenses and a mirror, as shown in Fig. 1(c). It generates a light sheet with 19 mm wide and 1.2 mm thick at the inducer.

Dioctyl phthalate (DOP) particles of about 0.6 μm in mean diameter were used as tracer particles. The tracer particles were generated using an aerosol atomizer (TSI Model 9306), and were supplied through a pipe of 5 mm in outer diameter located at 300 mm upstream from the inducer leading edges.

Here, it was considered that the wake effects behind the light sheet projector and the pipe for seeding particles were little owing to the contraction of the suction pipe and according to the following PIV results.

A glass window of 16 mm in diameter was mounted on a shroud casing to observe the flow. Particle images with 1008 × 1016 pixels and 8-bit resolution were captured using a CCD camera (KODAK MEGAPLUSE ES1.0) equipped with a lens (NIKON Micro Nikkor 105 mm f/2.8), and the images were stored in a PC through a frame-grabber board (EPIX PIXCI-D).

The sampling rate of a pair of images was about 3 Hz or every 100 revolutions, to keep the optical elements of the projector with low temperature, using a non-contact displacement sensor and a preset counter as the external trigger signal as shown in Fig. 1(a). A delay pulse generator was used so that measurements could be performed at arbitrary specified impeller blade phases. The time interval between double pulses was 2 ㎲ using a laser controller.

2.3 Phase Locked Measurement

The measurement was performed at the root-mean-square (RMS) radius of inducer. The blade pitch was 28.3 mm at the RMS radius of 67.6 mm. Since the window diameter was small against the blade pitch, the phase locked measurement was performed to obtain a velocity field over one blade pitch as shown in Fig. 2. Dotted circles indicate the observation areas, and solid rectangles indicate the effective areas for the evaluation of velocity vectors in consideration of the curvature effect. The phase was shifted every 20% blade pitch as shown by eight color rectangles in Fig. 2. Then, a velocity field over one blade pitch can be constructed by connecting eight velocity fields.

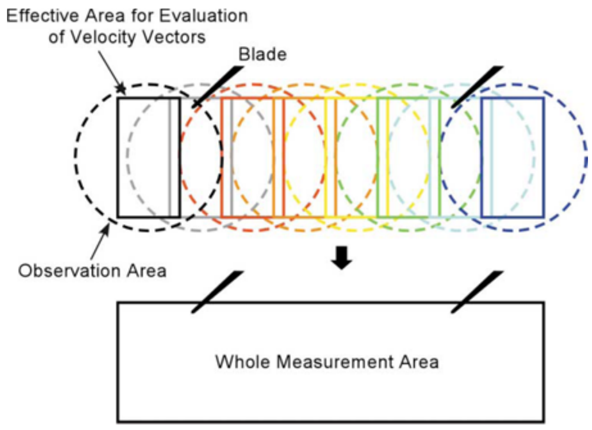


Fig. 2. Phase locked measurement technique.

2.4 Data Processing

The instantaneous velocity vectors were evaluated based on a cross-correlation method (Hayami et al., 1995) with 31 × 31 pixels of interrogation window. And the phase-averaged velocity vectors were evaluated based on the average correlation method (Meinhart et al., 1999) and a sub-pixel processing. Those were calculated from 100 instantaneous velocity vectors. Finally, the velocity field over one inducer blade pitch was obtained based on those eight phase-averaged velocity vector fields.

3. Experimental Results and Discussions

3.1 Compressor Characteristics

The characteristic curves of the compressor are shown in Fig. 3. The ordinate P_4 / P_0 is the total pressure ratio, and the abscissa G/G^* is the ratio of the mass flow rate to the choked flow rate in the suction pipe. The parameter M_t is the corrected speed or the nominal Mach number based on the inducer tip speed and the inlet stagnation temperature. The measurement was performed at the test point near the compressor-peak-efficiency (CP) operating point of $M_t = 1.041$ as shown in Fig. 3. The rotor speed was 17,940 rpm, and the pressure ratio was 5.2.

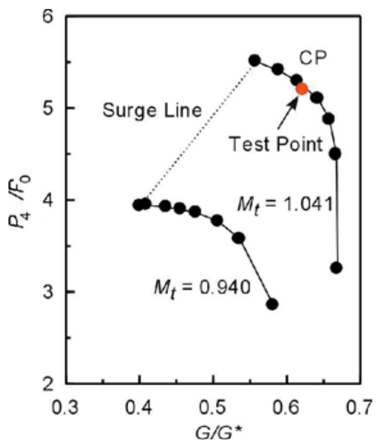
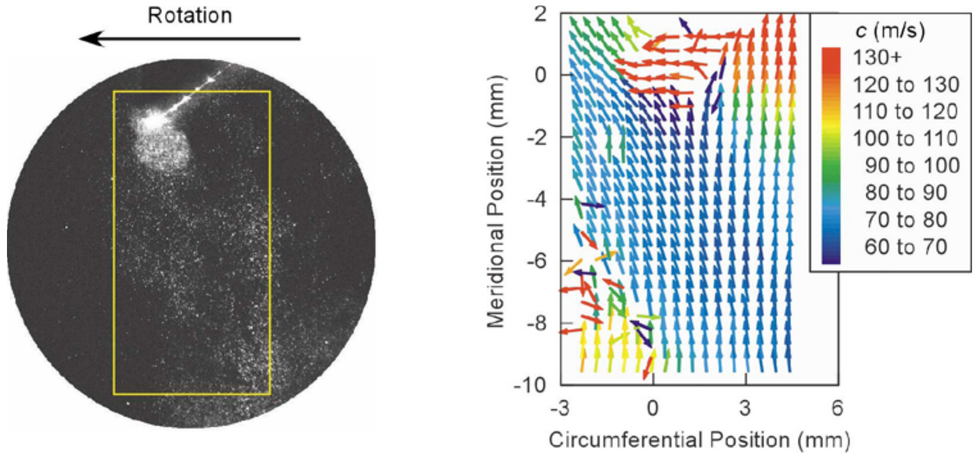


Fig. 3. Compressor characteristics.

3.2 Instantaneous Velocity Field

Figure 4(a) shows a typical particle image obtained at the second phase area from the left in Fig. 2. Thus, one blade leading edge is recognized at the top of the image. The rotational direction of the blade is from the right to left. The direction of fluid flow and illumination is from the bottom to top. The image area was 710 pixel in diameter, and the effective area was 300 × 580 pixels as shown in Fig. 4. The spatial resolution was 22.5 μm/pixel.

Figure 4(b) shows the instantaneous velocity vector field. The origin of the map corresponds to the blade leading edge. The velocity vectors near the inducer blade were obtained well. However, the erroneous vectors are recognized due to rare particles at the lower left area in Fig. 4(a).



(a) typical particle image (b) instantaneous velocity field

Fig. 4. Typical particle image and the instantaneous velocity field.

3.3 Phase Averaged Velocity Field

To confirm validity of the phase locked measurement technique, Figure 5 shows the distributions of the meridional velocity c_m and the absolute flow angle a including all overlapped data at 3.3 mm upstream from the inducer leading edges. In the figure, SS means a suction surface of blade, and PS means a suction surface of blade. The data were all connected smoothly, and the jitter calibration of trigger pulse signals was evaluated based on the fluctuation of blade locations in every images corresponding to Fig. 4(a). The confidence interval of the mean blade location for the confidence coefficient of 0.9 was 1.4 pixel for the present 100 data averaging, and it is equivalent to 0.1% of the blade pitch. Thus, the present measurement technique enabled to obtain a velocity field over one inducer blade pitch.

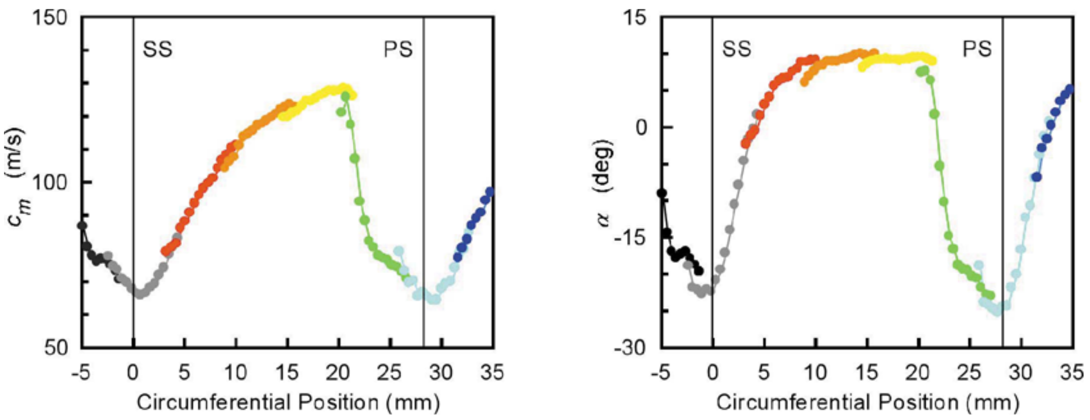


Fig. 5. Distributions of meridional velocity c_m and absolute flow angle a, 3.3 mm upstream from inducer leading edges. SS: suction surface of blade, PS: pressure surface of blade.

Figure 6 shows a vector field of the absolute velocity c, evaluated directly from images. Here a color indicates a vector magnitude, and an arrow indicates an absolute flow direction. The maximum velocity in the present map was 131.5 m/s, where the maximum particle displacement was 11.7 pixel. A strong change in both velocity and flow angle was recognized along the suction surface of a blade.

The relative velocity vectors were calculated by vectorial subtraction of the peripheral velocity of the impeller. Figure 7 shows the relative velocity vector field and the contour map of relative flow Mach number M_r, based on the inlet stagnation temperature. In the present experiment, the peripheral velocity of the impeller was 127 m/s, and the local sound velocity was 156 m/s. The high subsonic fluid flow was once accelerated along the blade suction surface, and then a shock wave was generated behind the supersonic zone.

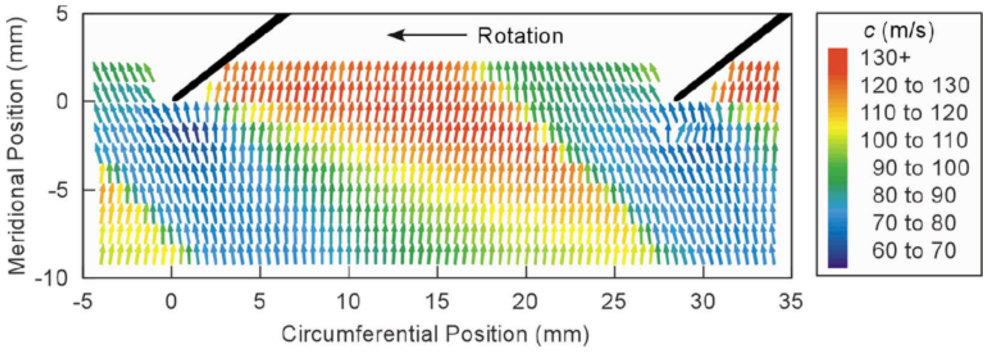


Fig. 6. Absolute velocity vector field.

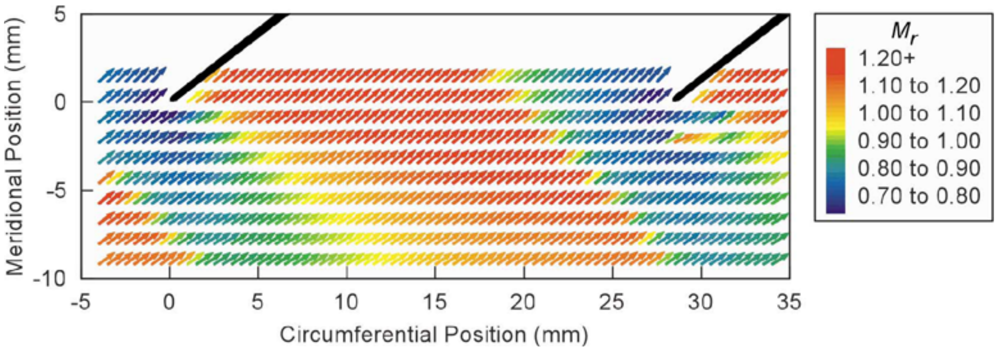


Fig. 7. Relative velocity vector field and contour map of relative flow Mach number.

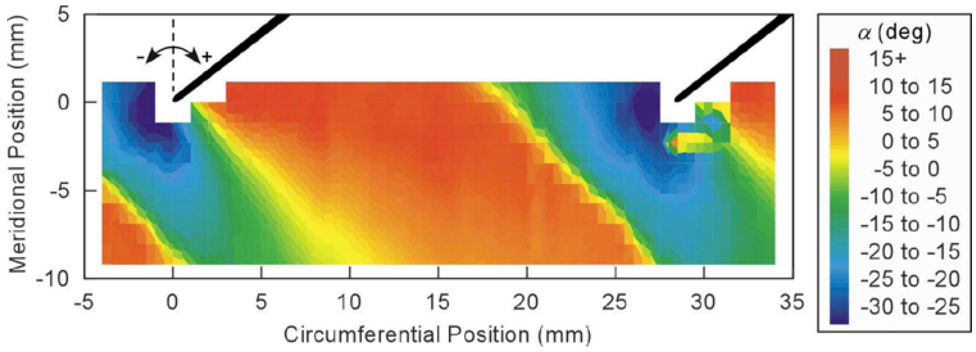


Fig. 8. Contour map of absolute flow angle.

Figure 8 shows the contour map of absolute flow angle a, based on the absolute velocity vector field shown in Fig. 5. A strong change in absolute flow angle was recognized along the suction surface of a blade, and the location agreed well with one of the shock wave in Figs. 5 and 7. That is, the existence of a shock wave can be recognized by the contour map of absolute flow angle directly before the evaluation of the relative flow field.

4. Conclusion

A particle image velocimetry (PIV) was successfully applied to a flow measurement in a transonic centrifugal impeller. The velocity field over one blade pitch in the inducer was visualized using the phase locked measurement technique, and also a shock wave generated on the suction surface of a blade was presented clearly from the contour maps of relative flow Mach number and the absolute flow angle. The validity of the phase locked measurement technique was confirmed based on both the magnitude and direction of absolute velocity and based on the jitter calibration of the trigger pulse signals.

Acknowledgments

The present work has been carried on partly under a Grant-in-Aid for Scientific Research in 1999-2000 (No. 11650178).

References

Hayami, H., Chen, D. and Koso, T., Application of Image Processing Measurement to a Relative Flow in a Pump-Turbine Runner, Journal of Flow Visualization and Image Processing, 2 (1995), 75.

Hayami, H., Research and Development of a Transonic Turbo Compressor, Turbomachinery Fluid Dynamics and Heat Transfer, (1998), 63, Marcel Dekker, Inc.

Hayami, H., Senoo, Y. and Ueki, H., Flow in the Inducer of a Centrifugal Compressor Measured with a Laser Velocimeter, ASME Journal of Engineering for Gas Turbines and Power, 107-2 (1985), 534.

Meinhart, C. D., Wereley, S. T. and Santiago, J. G., A PIV Algorithm for Estimating Time-Averaged Velocity Field, Proc. Optical Methods and Image Processing in Fluid Flow, 3rd ASME / JSME Fluids Engineering Conference (San Francisco), (1999), 1.

Tisserant, D. and Breugelmans, F. A. E., Rotor Blade-to-Blade Measurements Using Particle Image Velocimetry, ASME Journal of Turbomachinery, 119-2 (1997), 176.

Wernet, M. P., Development of Digital Particle Imaging Velocimetry for Use in Turbomachinery, Experiments in Fluids, 28 (2000), 97.

Author Profile

Hiroshi Hayami: He received his Ph.D. (Eng) from Kyushu University in 1976. He has been a faculty member of Institute of Advanced Material Study (former Research Institute of Industrial Science till 1987), Kyushu University since 1973, and currently a professor. His research interests are R&D of transonic centrifugal compressors, micro gas turbines and PIV and PSP techniques for rotating machinery.

Masahiro Hojo: He received his BSc (Eng) from Kyushu University in 1998, and then received his MSc (Eng) in 2000. Now he studies for his PhD (Eng) in Kyushu University.

Shinichiro Aramaki: He received his BSc (Eng) from Kyushu Institute of Technology in 1993, and his MSc (Eng) from Kyushu University in 1995. He became a research associate in 1995 at Kyushu University. His research interests are flow visualization and measurement of internal flow in turbomachinery.