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Application of PIV in a Transonic Centrifugal Impeller

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Abstract A particle image velocimetry (PIV) was applied to a flow measurement in a transonic centrifugal impeller. A phase locked measurement technique every 20 % blade pitch enabled a reconstruction of a velocity field over one blade pitch. The measured velocity field at the inducer of impeller clearly showed a shock wave generated on the suction surface of a blade.

Keywords: Centrifugal Compressor, Centrifugal Impeller, Particle Image Velocimetry, Phase Average, Shock Wave

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).

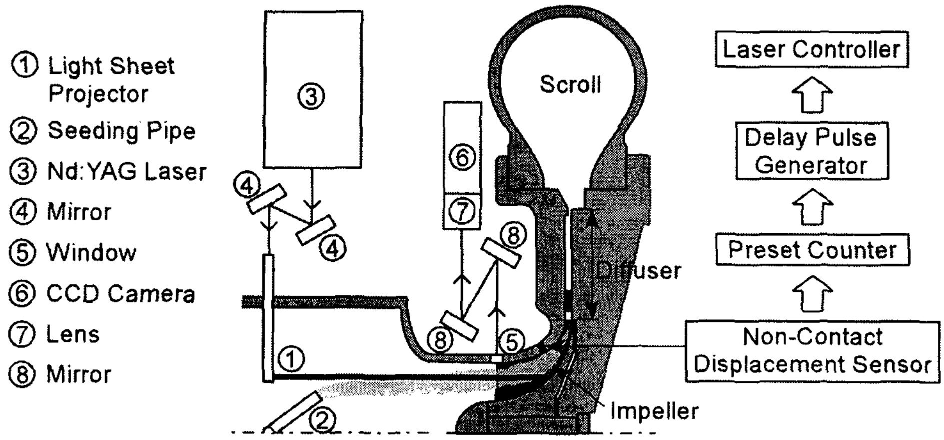
Particle image velocimetries (PIVs) have major features of both laser velocimetries and optical visualization techniques. And they are very attractive owing to the feasibility of simultaneous and multipoint measurement. PIVs offer an extensive velocity field in an extremely shorter measurement time than laser velocimetries. 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 et al., 1997), and a flow with a passage shock wave in a transonic axial compressor (Wernet, 1997).

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.

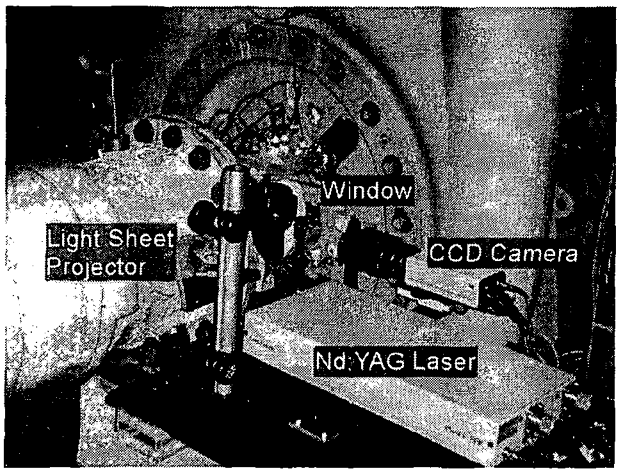
Experimental Apparatus and Procedure

A centrifugal compressor was tested in a closed loop with HFC134a gas at 17,940 rpm. The pressure ratio was 5.2. The meridional profile of the test compressor is shown in Fig. 1a. 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 diameter was 172 mm. 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).

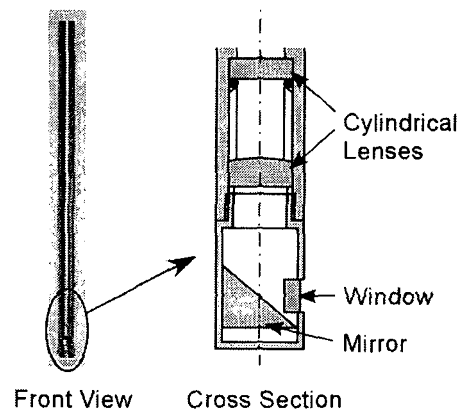
The PIV measurement system, shown in Figs. 1a and 1b, was based on a double-frame PIV technique with a double-pulsed Nd:YAG laser (Continuum Minilite II) with 25 mJ. A pulsed laser beam was reflected by two mirrors, and passed through a light sheet projector of 10 mm in outer diameter and 200 mm long. 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 is consisted of two cylindrical lenses and a mirror, as shown in Fig. 1c, generating a light sheet with 19 mm wide and 1.2 mm thick at the inducer.



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



(b) experimental apparatus



(c) light sheet projector

Fig. 1 Experimental apparatus.

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 diameter located at 300 mm upstream from the inducer leading edges.

A glass window of 16 mm in diameter was mounted on a shroud casing to observe particles. Particle images were captured using a CCD camera (KODAK MEGAPLUSE ES1.0) with 1K x 1K pixels and 8-bit resolution, which was 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. A digital 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 μs using a laser controller.

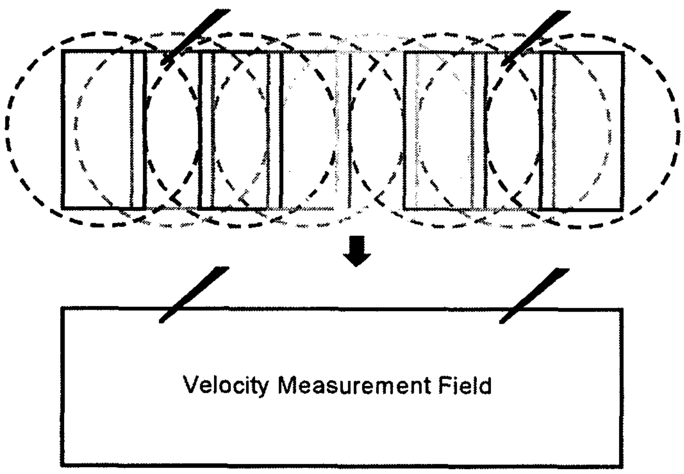
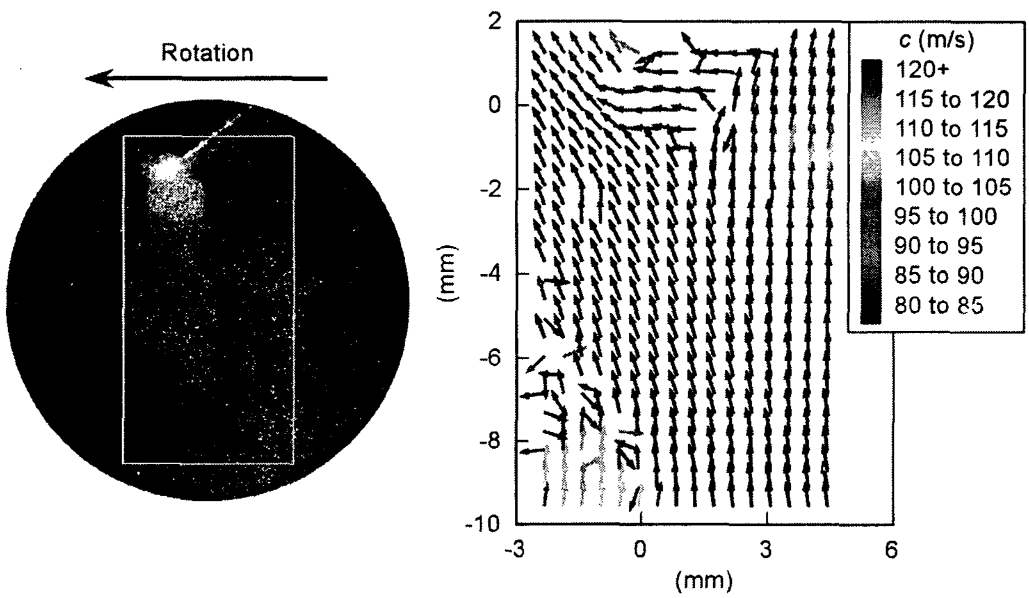


Fig. 2 Phase locked measurement.



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

Fig. 3 A typical particle image and the instantaneous velocity field.

The instantaneous velocity vectors were evaluated based on a cross-correlation method (Hayami, 1995) with 31 x 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. And finally, the velocity field in a velocity field over one inducer blade pitch was obtained based on those phase-averaged velocity vector fields.

Experimental Results and Discussions

The measurement was performed at a root-mean-square (RMS) radius of the 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 technique was applied every 20 % blade pitch as shown in Fig. 2. Figure 3a shows a typical particle image obtained at the second phase area from the left in Fig. 2. Thus, a blade is recognized at the top of the image. The rotational direction of the blade is from right to left. The direction of fluid flow and illumination is from bottom to top. The image area

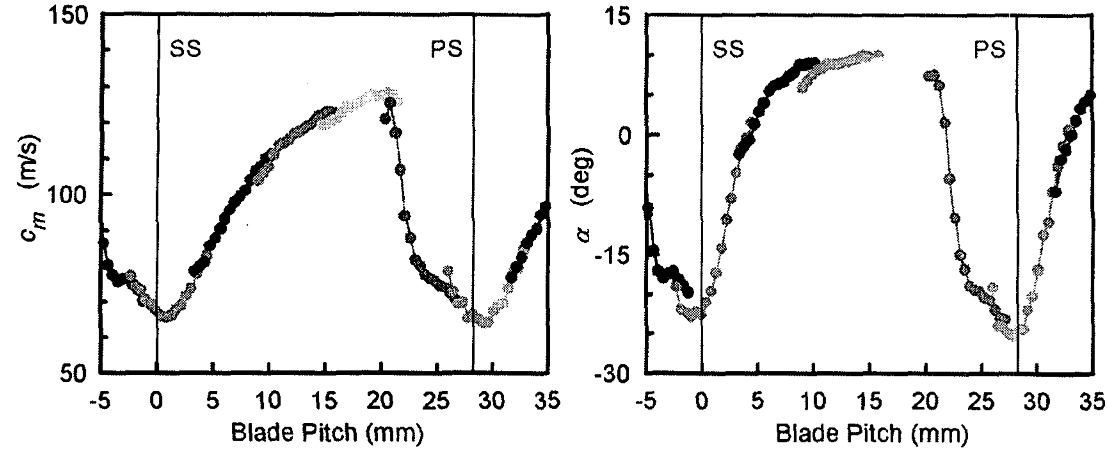


Fig. 4 Distributions of axial velocity and absolute flow angle.

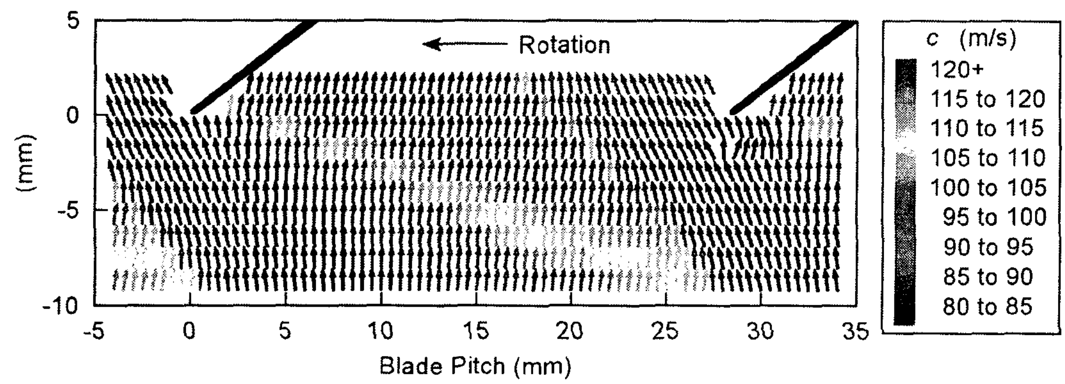


Fig. 5 Absolute velocity vector field.

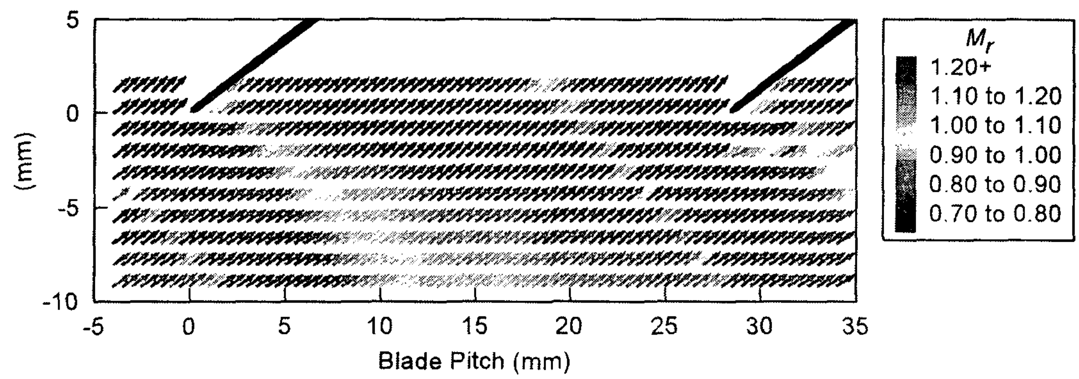


Fig. 6 Relative velocity vector field and contour map of relative flow Mach number.

was 710 pixel in diameter. However, in consideration of the curvature effect, the effective area for the evaluation of velocity vectors was 300 x 580 pixels as shown in Fig. 3. Then, the whole velocity measurement field over one blade pitch could be reconstructed as shown in Fig. 2. The spatial resolution was 22.5 μm/pixel. Figure 3b shows the instantaneous velocity vector field. 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. 3a.

To confirm validity of the phase locked measurement, Fig. 4 shows the distributions of the axial velocity c_m and the absolute flow angle α including all overlapped data at 3.26 mm upstream from the inducer leading edges. The data were all connected smoothly. Then, the present measurement technique enabled to obtain a velocity field over one inducer blade pitch.

Figure 5 shows the absolute velocity vector field evaluated directly from images. Here a color indicates a vector magnitude, and an arrow indicates an absolute flow direction. The maximum velocity was 131.5 m/s, where the maximum particle displacement was 11.7 pixel. A strong changes in velocity and flow angle was recognized perpendicular to the suction surface of a blade.

The relative velocity vectors were calculated by vectorial subtraction of the peripheral velocity of the impeller. Figure 6 shows the relative velocity vector field and the contour map of relative flow Mach number based on the inlet stagnation temperature. The high subsonic fluid flow was once accelerated along the blade suction surface, and then a shock wave was generated behind the supersonic zone.

Conclusion

A PIV was successfully applied to a flow measurement including a shock wave in a high speed rotating impeller. The existence of shock waves can be recognized from the contour map of relative flow Mach number.

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