

Study of Flow Patterns in Vaneless Diffusers
of Centrifugal Compressors using PIV

by

Nobutaka Hayashi, Masaharu Koyama, Ichiro Ariga

Chiba Institute of Technology
Mechanical Engineering Department
2-17-1 Tsudanuma, Narashino-shi
Chiba, Japan 275-0016

Abstract

In centrifugal compressors, rotating impellers give energy to fluid. And, diffusers are some of the main components for the pressure recovery function. Therefore, in order to improve their performance, it is important to understand the aspect of the flow field in diffusers in detail. However, such diffusers generally have very small widths. Due to the occurrence of adverse pressure gradients in diffusers, secondary flows are generated, making the flow fields more complicated. In addition, skewed boundary layers form on wall surfaces. It is also known that flow fields become more complicated, which leads to the generation of rotating stalls as flow rate reduces. For this reason, it is necessary to clear flow fields in order to better understand diffuser characteristics. In this study, PIV was used for measurement. Pressure was also measured using a semi-conductor pressure transducer to obtain data on static pressure fields. This experiment was performed using an open loop centrifugal compressor without a scroll casing. The test rig used a parallel-wall diffuser with the following dimensions: width 0.017m; inlet diameter 0.345m; outlet diameter 0.862m. The impeller had the following dimensions: inlet width 0.032m; outlet width 0.017m; inlet diameter 0.16m; outlet diameter 0.345m. The corrected revolution of the impeller was kept at 2000rpm during the experiment. Flow rate was measured with a pressure transducer located at the inlet nozzle of the compressor and controlled by a butterfly valve.

1. INTRODUCTION

In centrifugal compressors, diffusers are some of the main components for the pressure recovery function, and they play an important role in the performance of compressors. Generally, as flow rate reduces, compressors have a limited operation range, due to occurrence of self-exciting phenomena that result in machine fracture, like surge and rotating stall. The distinction between these two phenomena is decided by the location and flow rate at which they occur. During surge, the entire compressor system, including the discharge duct, oscillates. On the other hand, rotating stall occurs only in some components of the compressor, and the flow rate is higher than the surge reveals. It can be said that a compressor's operation range is limited by rotating stall. There are two types of rotating stall: diffuser rotating stall and impeller rotating stall. In most cases, diffuser rotating stall is problematic because the amplitude of pressure fluctuation it causes is larger than that during impeller rotating stall.

Rotating stall in vaneless diffuser is caused by complicated flow fields. With the decrease in flow rate, the radial velocity component decreases, and the boundary layer finally separates. In the meantime, because the impeller continues to rotate at a constant rotational speed, tangential velocity component exists without separation of the boundary layer. Therefore, the separation region begins to rotate in the tangential direction.

Many investigators have investigated unsteady flow in the vaneless diffuser for decades. For example, there is the early work of Jansen(1964), who concluded with the theoretical approach that the flow becomes unstable when reverse flow occurs. Watanabe and Konomi et al(1994) measured the velocity of the entire flow field of a vaneless diffuser using hotwire with the phase locked method; the hot wire measurement was triggered by the signal of the pressure fluctuation caused by the rotating stall. But neither the generation of rotating stall nor its mechanism has been made clear. It is important to understand these matters clearly in order to widen the operation range of the compressors. So it still remains a challenging task.

PIV is a measurement that can obtain the both velocity information and image that visualize the flow field. Recently, the rapid development of PIV has accompanied with an increase in its utilization for the turbomachinery. For example, Oakes and Fleeter(1997) used PIV to measure the flow field in the impeller of centrifugal compressor during the impeller rotating stall. Wernet and Bright (1999) used PIV for a complex flow field in the vaneless diffuser of a high speed centrifugal compressor during surge.

In this study, we attempted to measure transient flow field in the vaneless diffuser of a centrifugal compressor with PIV utilizing a comparatively simple system. This study was aimed to investigate the possibility of using PIV for unsteady flow field in vaneless diffuser. Therefore, the flow rate at which the flow field becomes most unstable was targeted.

2. EXPERIMENT APPARATUS

This experiment was performed using an open loop centrifugal compressor without a scroll casing. The test apparatus is shown in Fig.1. The test rig used a parallel-wall diffuser with the following dimensions: width 0.017m; inlet diameter 0.345m; outlet diameter 0.862m. The impeller had the following dimensions: inlet width 0.032m; outlet width 0.017m; inlet diameter 0.16m; outlet diameter 0.345m. The corrected revolution of the impeller was kept at 2000rpm during the experiment. Flow rate was measured with a pressure transducer at the inlet nozzle of the compressor and controlled by a butterfly valve. The measurement part of the diffuser were designed so that they could be removed easily and replaced for PIV and static pressure measurement. The schema of measurement section for PIV and static pressure measurement is shown in Fig.2. The interrogation window (866x890 pixel) for PIV data processing is shown in Fig.3 .

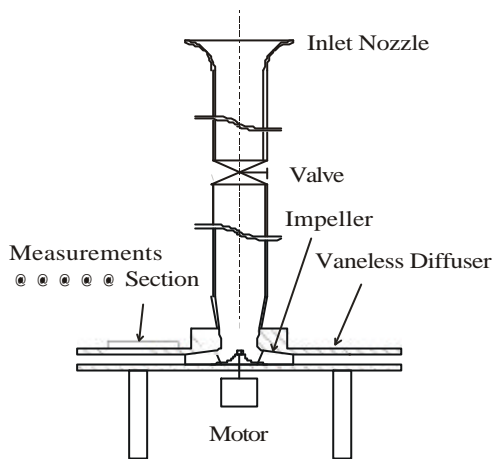


Fig.1 Test apparatus

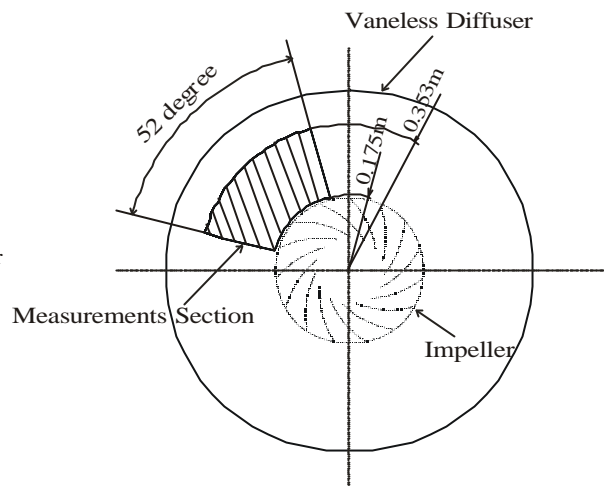


Fig.2 Measurements section

The PIV system consists of a Laser Pulse Synchronizer, a CCD camera, an ND:Yag Laser, and a personal computer, as shown in Fig.4. 1.0 micron tracers produced by a SAFEX Fog Generator were introduced into the compressor inlet flow. A laser sheet was introduced from the outlet of the diffuser parallel to the diffuser wall. For static pressure measurement Toyota PD104K semiconductor pressure transducers were used. The signals from the pressure transducer were sampled by a 16bit A/D converter, which was connected to a personal computer.

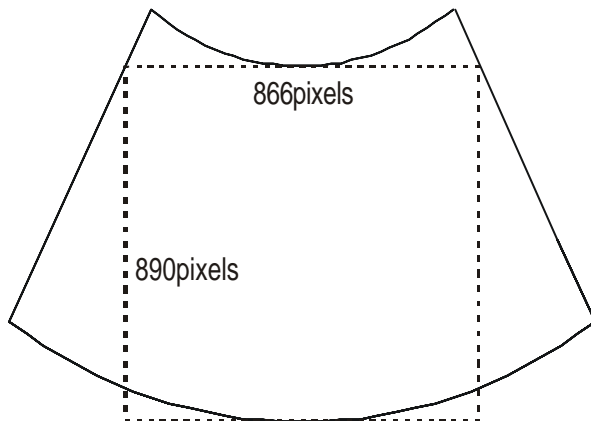


Fig.3 Interrogation window for data processing

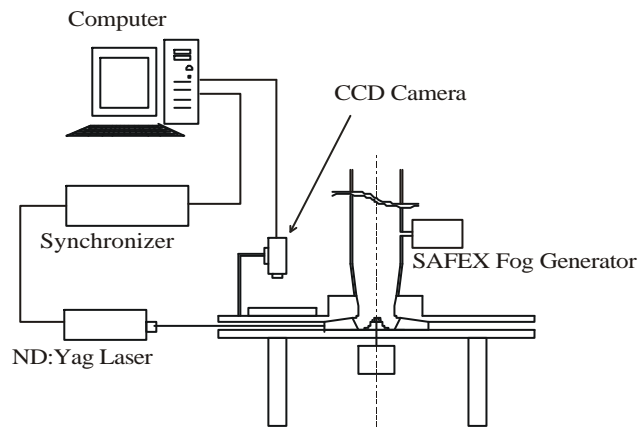


Fig.4 PIV system

3. RESULT AND DISCUSSION

3-1. DIFFUSER PERFORMANCE

The diffuser performance was estimated from the pressure recovery coefficient C_p and flow coefficient F as shown below.

$$C_p = \frac{p_2 - p_1}{\frac{1}{2} \rho u^2}, F = \frac{Q}{Au}$$

p_1 : static pressure of diffuser inlet ($r_1 / r_0 = 1.1$)

p_2 : static pressure of diffuser outlet ($r_1 / r_0 = 2.0$)

ρ : density of air

u : impeller tip speed

Q : corrected flow rate

A : impeller outlet area

r_0 : impeller radius

r_1 : distance from center of the diffuser

Fig.5 shows performance curve of the diffuser, and the performance drop rapidly at $F=0.184$ and $F=0.175$.

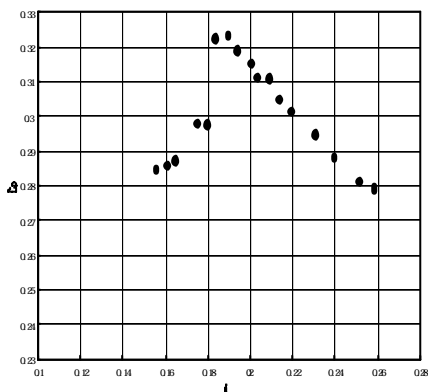


Fig.5 Performance curve of the diffuser

To understand the phenomena in the diffuser in greater detail, the static pressure measurement was carried out at $r_1/r_0=2.0$. Fig.6 shows the pressure fluctuation and the result of FFT analysis at $F=0.184, 0.175, 0.174, 0.16$. As the flow rate reduces, the periodic pressure pattern is revealed at $F=0.174$. And at $F=0.16$ it finally changes to pressure pattern shown in Fig.6. However, it is clear from the result of the FFT analysis that it still keeps a periodicity of around 4Hz. PIV measurement was carried out at the lowest flow rate, $F=0.16$.

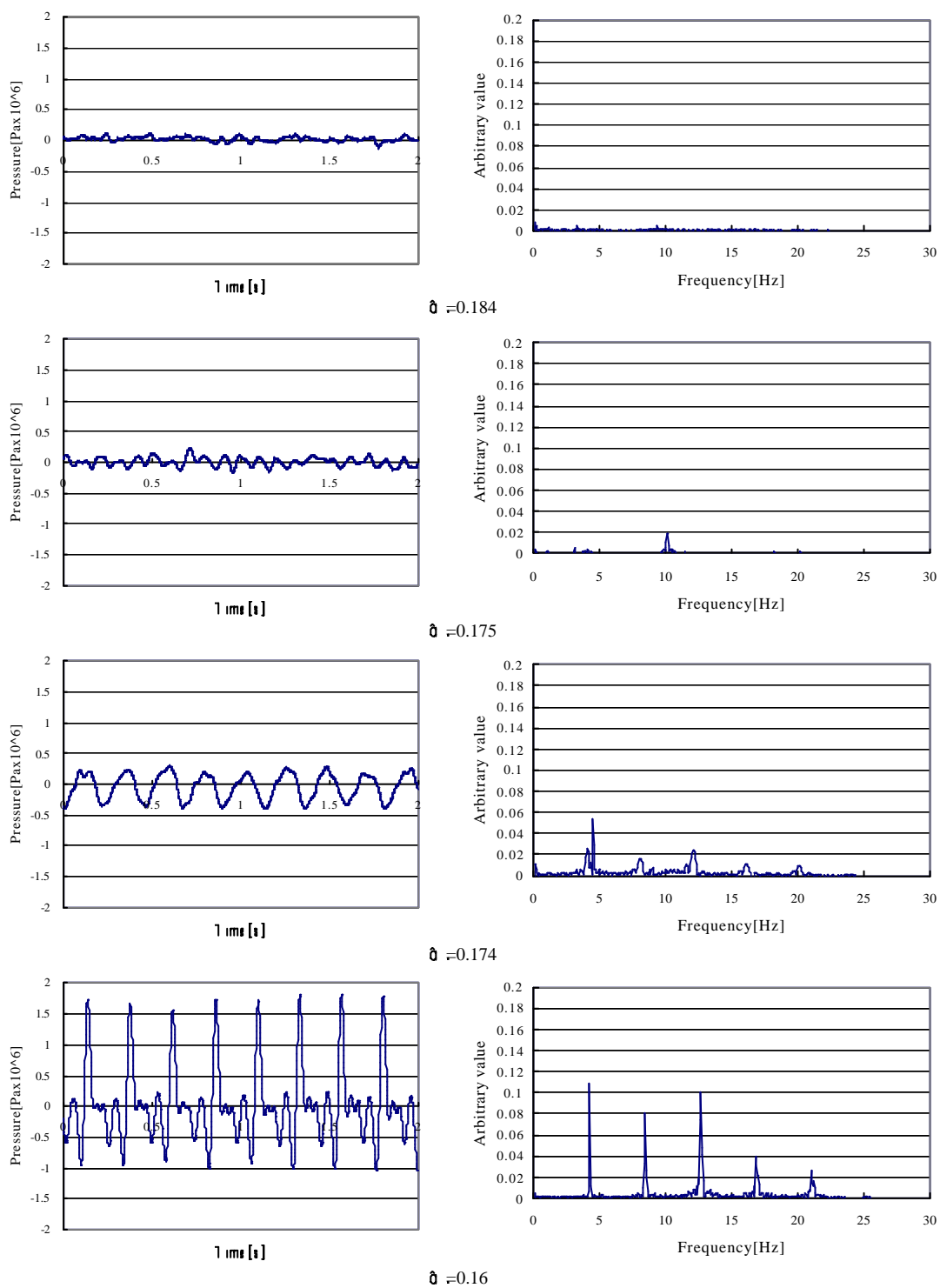


Fig.6 Pressure fluctuation and result of FFT analysis

3-2. NUMBER OF THE STALL REGION

To estimate the propagation speed of the stall region at $F=0.16$, the cross-correlation of the pressure fluctuation of two different points that were located in different circumferential locations was calculated (Fig.7, Fig.8). The number of stall regions, m , is calculated with the following method. The number of stall regions at $F=0.160$ turned out to be 1.

$$m = \frac{\theta \times 360}{\theta'} \times \frac{1}{\tau}$$

τ : timelag between two fluctuation (0.031s)

θ' : timelag between one peak and next peak (1/4.272s)

θ : degree between two points (45 degree)

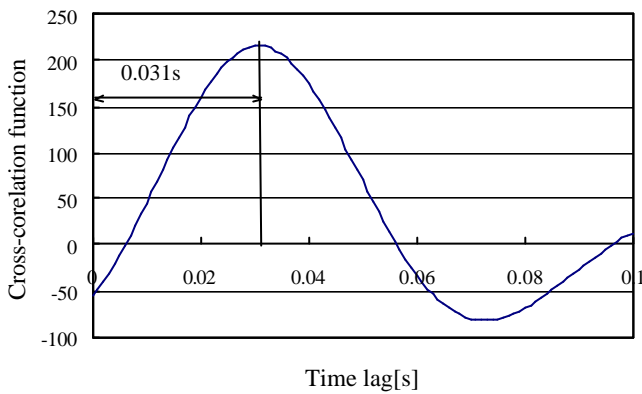


Fig.7 Cross-correlation between point 1 and 2

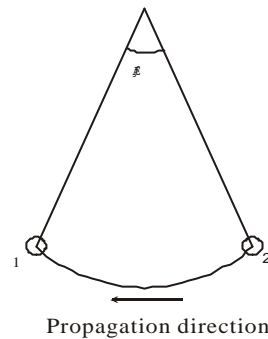


Fig.8 Location of point 1 and 2

3-2. PHASE LOCKED MEASUREMENT WITH PIV

The sampling time for PIV measurement is decided by the 4 timing factors; camera strobe out, camera exposure, camera digital video image output and laser pulse. And taking these four timing factors into account, its maximum repetition rate is $66275\mu s$. That means this system can measure the velocity fluctuation including frequency up to only 7.5Hz.

To avoid this situation phase locked measurement based on the signal from the pressure transducer was performed. A trigger signal was made as shown in Fig.9. A voltage of 5v was generated at the peak value of pressure, and the PIV system was triggered by this signal. The measurement was carried out 20 times and the data was averaged.

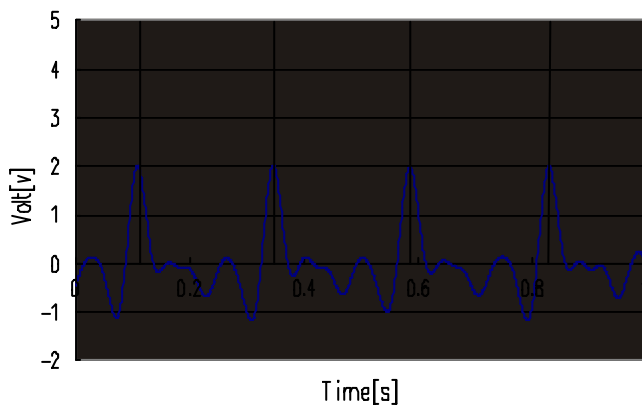
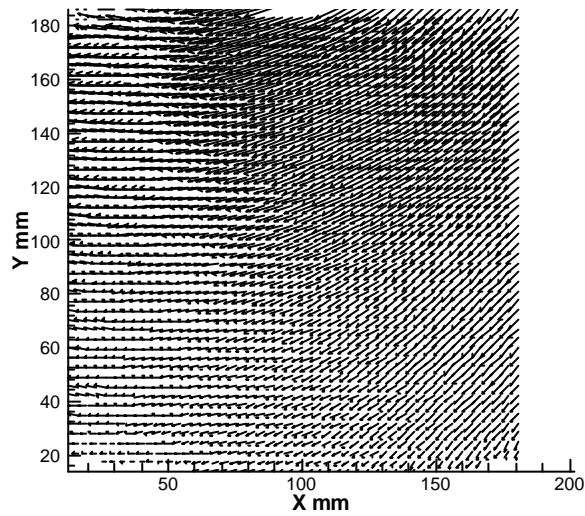


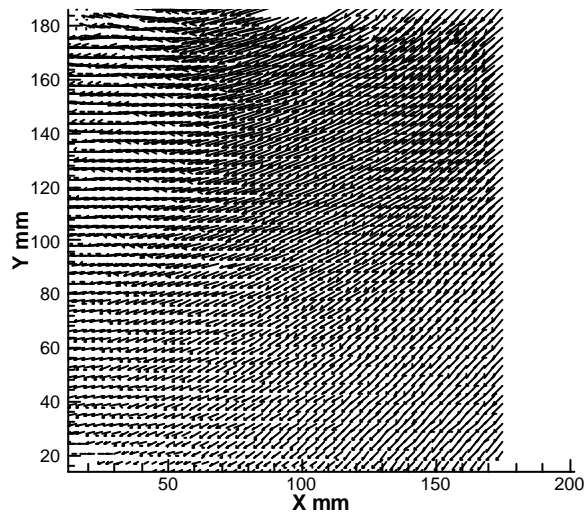
Fig.9 Trigger signal

A pressure transducer for the trigger signal was attached to the hub side of the diffuser wall. The trigger timing was delayed by 0,10,20,30,40,50, and 60 ms.

Fig.10 shows the velocity vector of timing delay of 0ms and 10ms. However, it is difficult to recognize the difference. Therefore, the velocity contours for timing delays of 0,10,20,30,40,50, and 60 ms were drawn as shown in Fig.11. As the timing delays, the contour line near the diffuser outlet distorts. Fig.11 (a) shows symmetrically shape of velocity contour for right and left. In Fig11 (b) (c) it changes asymmetrical. Finally it becomes symmetric again in Fig.11 (d). And this pattern repeats again in Fig.11 (e) (f) (g). From this result, it is clear to see that stall region intrudes into the diffuser because of adverse pressure gradient and rotates. The stall region can be described ring shape.

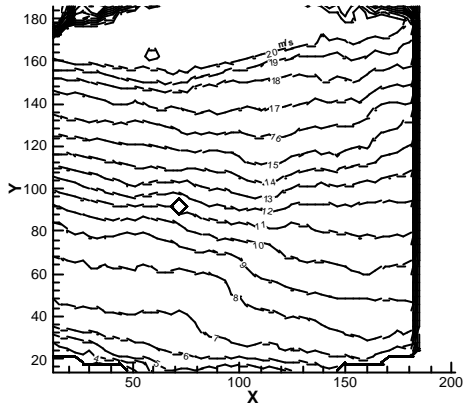


(a) 0ms

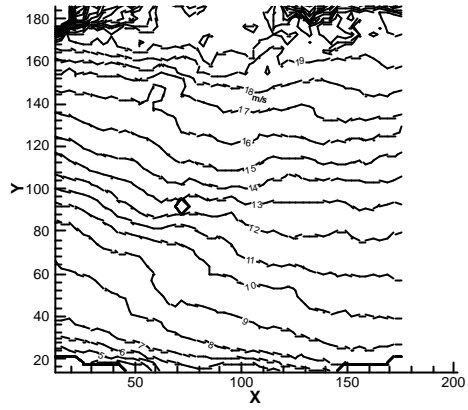


(b) 10ms

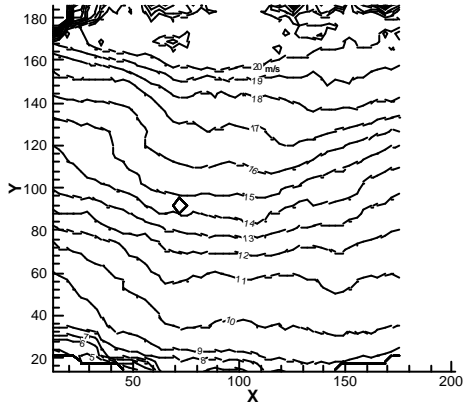
Fig.10 Velocity vector



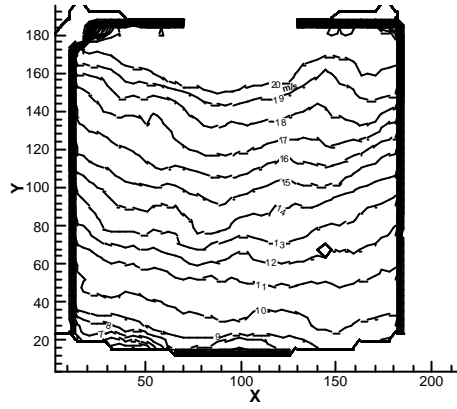
(a) 0ms



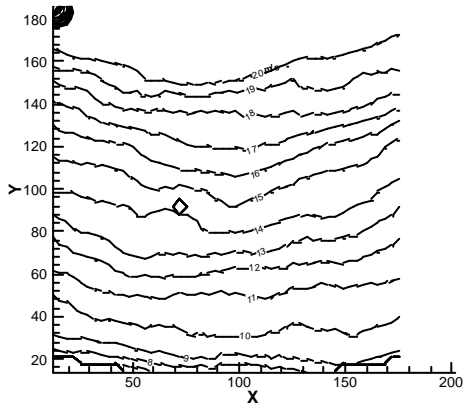
(b) 10ms



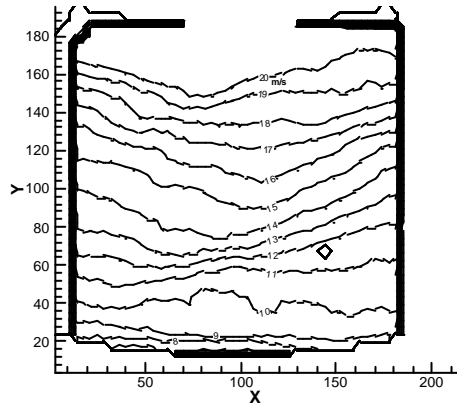
(c) 20ms



(d) 30ms



(e) 40ms



(f) 50ms

Fig.11 Velocity contour

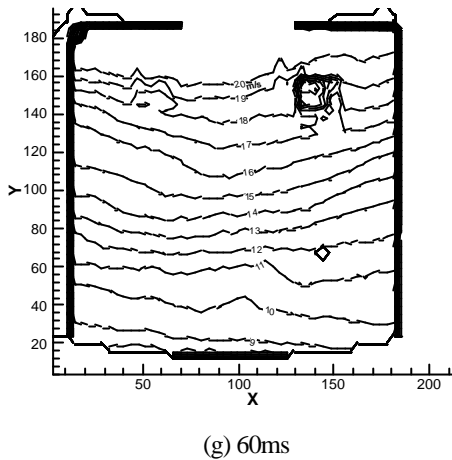


Fig.11 Velocity contour

4. CONCLUSION

Velocity measurements in the vaneless diffuser of a centrifugal compressor using PIV were carried out during the diffuser rotating stall. Tracer was seeded in the inlet flow and laser sheet was introduced from the outlet of the diffuser parallel to the diffuser wall. A trigger signal was generated based on the pressure fluctuation of the rotating stall, to obtain the trigger timing for phase locked measurement.

From the test result, it was proven that the stall region intrude into the diffuser because of an adverse pressure gradient, and PIV with phase locked averaging is well suited for the velocity measurement in the unsteady flow field with periodic flow patterns like rotating stall.

As mentioned before in the introduction, this work was aimed at investigating the possibility of PIV for using it in unstable flow fields in vaneless diffuser. In addition, the final goal was to clarify the mechanism of the rotating stall and obtain enough information on the transient process from stable to unstable flow fields, in order to develop a stall suppressing system.

5. REFERENCE

Jansen, W. (1964). "Rotating Stall in Radial Vaneless Diffuser", ASME JOURNAL OF BASIC ENGINEERING, December, pp.750-758

Oakes, W. C., Fleeter, S. (1997). "Characterization of Centrifugal Compressor Rotating Stall with Particle Image Velocimetry", 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Seattle, WA, July 6-9, 1997.

Watanabe, H., Konomi, S. and Ariga, I. (1994). "Transient Process of Rotating Stall in Radial Vaneless Diffuser", ASME, International Gas Turbine and Aeroengine Congress and Exhibition, The Hague, Netherlands, June 13-16, 1994.

Wernet, M.P. and Bright, M.M. (1999). "Dissection of Surge in a High Speed Centrifugal Compressor Using Digital PIV", 37th AIAA Aerospace Science Meeting and Exhibit, Reno, NV, January 11-14, 1999.