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A Novel Rapid and Multi-frame PIV Method for Measuring Supersonic Flow

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Abstract. PIV (Particle Image Velocimetry) technology is a transient, multi-point and non-contact speed measuring method of fluid dynamics, playing more and more important role in experimental fluid mechanics. The measurement of supersonic complex flow field has high requirements for PIV experimental configurations. In most of the PIV measurement systems, instant velocity field can be processed by getting only two consecutive images, which has very large restriction for the research of supersonic unsteady flow field. So we build up a PIV platform for measuring continuous flow field with high spatio-temporal resolution, several photos with ainterval of 100 ns could be obtained in this system, which greatly expand the application of PIV technology in supersonic unsteady flow field.

1. Introduction

PIV measurement is a transient, multi-point and non-contact speed measuring method of fluid dynamics, which has high measuring accuracy in general flow field[1]. Because of the supersonic flow's high speed, large gradient, compressibility and complex flow structure, it has great challenge to study the supersonic flow in experiment. Several articles have made detailed summary about the development and challenges of research on the supersonic flow with PIV technology.[2]In order to truly show the flow structures through PIV images, the tracer particles spread in the flow need to have good following and scattering features[4]; the laser light sheet need to have sufficient strength and repetition frequency simultaneously[5]; and a high resolution and frame rate are required for the CCD camera[6]. All in all, while achieving PIV images in a very short interval, some properties such as spatial resolution, accuracy and speed dynamic range should not be reduced, so better experimental configurations are required for the PIV system.

In recent decades, with the development of high-energy laser and CCD camera with short span frame time, the accuracy and speed range of PIV system have made a lot of progress. In most of the current PIV systems used in supersonic flow,two consecutive scattering images of particles can be acquiredand a transient velocity field distribution can be obtained after processing, which has been used successfully to measure flow velocitiesinmost of the flow. But for the research of supersonic unsteady flow, further research is limited with only one velocity field distribution.

In order to improve the speed range of the PIV measurement without having to reduce the light scattering intensity of the seeded flow, we designed a new generator to produce tracer particles of nanometer level, and then build up a PIV platform for measuring continuous flow field with high spatio-temporal resolution. Solid particle tracers of 50-nm-diameter TiO_2 are used as seeding material. The illumination is obtained by a quadruple-pulse Nd:YAG laser, and the particle scattering image is recorded by a four-channel HSFC PRO ultra-high speed enhanced camera. Several particle images with interval of hundreds of nanoseconds could be acquired in this PIV system, and continuous velocity distribution of the supersonic flow can be obtained after processing, which can provide strong technical support for research on supersonic steady and unsteady flow.

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2. Key Techniques and Methods

2.1 Introduction to the PIV Technology.

Theschematic of PIV measurement is shown in figure 1.Tracer particles move with the flow after particle seeding, the particles in the flow field is illuminated by pulse laser light with a certain time interval and then 2 images can be recorded by a high speed CCD camera. The cross-correlation performed by the image processing software yield the velocity distribution of the imaged flow field, and some characteristics of the field such as streamline, isovelocity and vorticity distribution can be obtained after further processing[7].

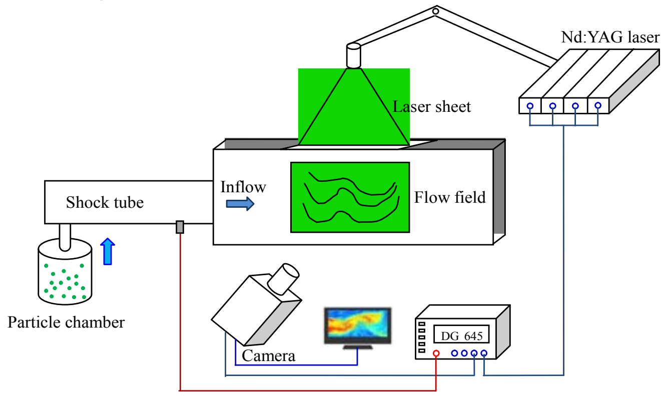

Fig.1 The Schematic of PIV Measurement

2.2 Tracer Particles and its Spraying Device

Particle seeding is accomplished by using a newly designed seeder containing TiO_2 particles of 50 nm crystal size. As is shown in figure 2, two copper filters with 0.2 mm apertures are placed in the c and d, and the powder particles are placed on the filter c before experiment. High pressure and dry gas flows into the a and b entrance, and then sprays into the tank from many holes of 2 mm.High pressure at the bottom of the dry gas from among a and b channel injection, and then from multiple aperture 2 mm holes into the tank, the particles are stirred, dispersed and lifted up by the rotating airflow with strong disturbance. As the pressure rises, the particles move upward and are filtrated through the d filter. Only small particles with a mean diameter of 0.1 μm are allowed to pass the exit of the tank and then are poured into the experimental section along a large diameter hose.

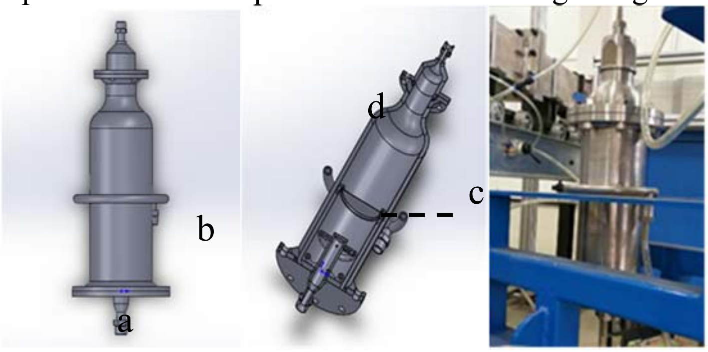

Fig.2 The Schematic and Photo of Tracer Particle Generator

2.3 Illuminating the Flow Field

In order to measure the high velocities of more than 1 km/s in the supersonic flow, a quadruple-pulse Nd:YAG laser is used to Illuminating the flow field as is shown in figure 3.Thelaser beam is given off exactly the same optical path by a beam combiner,and then a pulse light sheet of about 1 mm is generated to Illuminate the flow field with the help of the guarding light arm and optical lens group.The time interval between the four Nd:YAG lasers can be less than 0.5 μs with a pulse energy of 400 mJ, pulse-width 8ns, and divergence angle less than 1 mrad. The guarding light arm is very convenient to adjust the light path with seven flexible links, and the rate of energy loss rate is lower than 10%. Thus we have overcome the contradiction to improve the laser pulse energy and frequency at the same time.

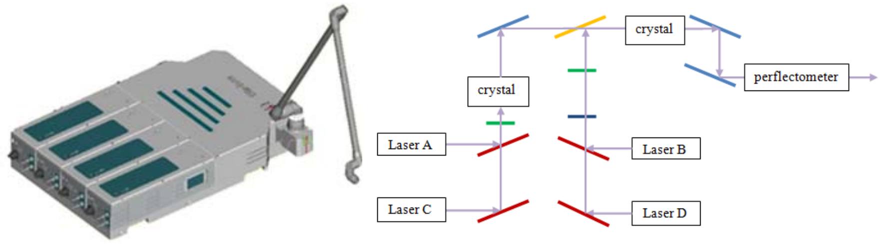

Fig.3 High Repetition Frequency Laser and its Work Functional Picture

2.4 Image Recording

We use the HSFC PRO ultra-high speed enhanced camera from the PCO company of Germanto view the illuminated flow field when the camera is mounted on the horizontal axis. This ultra speed camera system comprises animage splitter unit and four intensified CCD camera modules(1280*1024 pixels). Per channel respectively record a picture in one experiment with 3 ns shortest gating time and the time interval between the four channels can be set arbitrarily. Thus we have solved the problem of high resolution and high speed photography.

2.5 Timing Control System

The DG645 is a versatile digital delay/pulse generator that provides 4 pulse outputs and 8 delay outputs with a resolution of 5ps, meeting the needs of 100ns magnitude of the PIV system. Triggering of the synchronizer is accomplished by external trigger .As shown in figure 4, The 8 delay outputs correspond to the clock signal and Q signal of the 4 lasers. The start time and exposure time is set on the computer software connected with the high speed camera. The camera's four channels correspond respectively to four lasers and the exposure time covered every pulse time. To test and vertify the settings of the timing control system, we had a free-jet experiment. One of the scattering image of particles is shown in figure 5, the particles can be clearly seen and easy to identify.

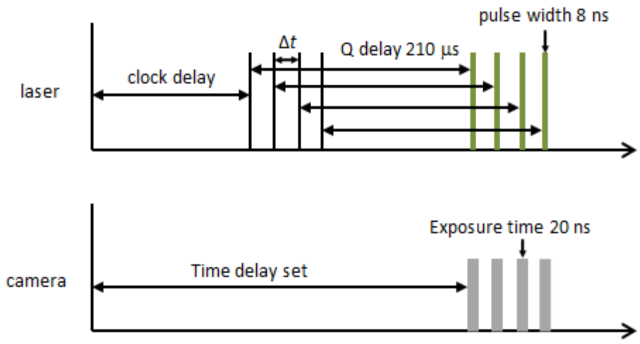

Fig.4The Schematic of Timing Control System

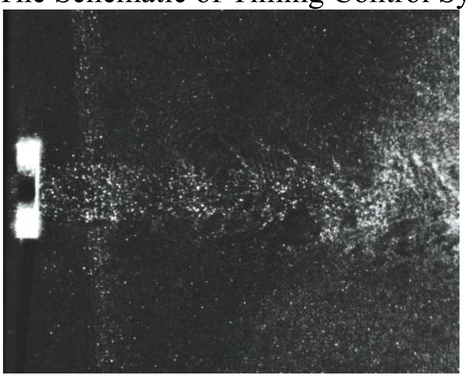

Fig.5Scattering Image of Particles from Free-jet Experiment

3. Innovation and Advantages of the PIV Measurement System

For the needs of measuring supersonic unsteady flow field, some key technologies of PIV measurement is broken through and a high precision PIV measurement system is developed. The main features are as follows:

1. Particle seeding is accomplished by using a newly designed fluidized-bed seeder containing 50 nm TiO_2 particles. The agglomeration of the particles is reduced and the particle concentration can be easily controlled, makes the following and scattering features meet the demand of measuring supersonic flow field.
2. A quadruple-pulse Nd:YAG laser with a pulse energy of 400 mJ and pulse-width 8ns is used to Illuminating the flow field, makes the flow has a higher brightness and is quasi-stationary with a short pulse time.
3. The exposure time of each CCD camera is about 10ns and the time interval of the adjacent pictures can be 100 ns magnitude, superior to the current level of about 1μs.
4. There are 4 particle images can be captured in one experiment and several continuous velocity field can be obtained after image processing, which can be used to study the evolution process of the flow field in 100 ns magnitude and this has broken through one of the bottlenecks of PIV technique.
5. For supersonic flow with a large dynamic range, different time interval (Δt, $2\Delta t$, $3\Delta t$) of particle images can be chosen to process aiming at different velocity area, so the dynamic range of PIV system is increased in a new way.

The rapid and multi-frame PIV systemfor measuring supersonic flow in this article has not only improved the speed limit to about 2000m/s, improved the dynamic range of PIV measurement, but also can be used to study the evolution process of the flow field in 100 ns magnitude, providing a new way to study the supersonic unsteady flow and the technology is so promising to be applied to the research of supersonic complex flow.

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