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On PIV to face new century

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Abstract: As one of the approaches to so called Ideal Observation & Measurement Technique (IOMT) for the fluid mechanics and the most practical one of Full Flow Field Observation and Measurement techniques (FFFOM) which will be the new generation of the experimental technique or instrumentation to across the new century, the recent progress and trend of Particle Image Velocimetry (PIV) & its application (including some works in China) are summarized and evaluated in some aspects. Also the facing requirements and further work of PIV for the complex & turbulent flows and the industrial applications are discussed. It will be the challenge for the PIV to face 21st century.

Key words: FFFOM; PIV; DPIV; SPIV; HPIV; 3Dt-3C; time history

面向新世纪的粒子图像测速

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摘要:一种综述粒子图像测速(Particle Image Velocimetry)的非接触、瞬时、动态、全流场的和本质上是直接的速度场测量技术,成为当今最实用和非常有潜力的流体力学全流场观测(Full Flow Field Observation & Measurement)技术。回顾和展望 PIV(包括 DPIV,SPIV,HPIV 等)及其应用的进展和前景。面临新世纪,PIV 技术有望最终攻克一个容积的三维速度场时间历程(3Dt-3C)的观测和推动流体力学进入十分活跃的新时期。

关 键 词:全流场观测;粒子图像测速;数字式粒子图像测速;体视粒子图像测速;全息粒子图像测速;三维三分量;时间历程

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0 Introduction

The spatial (vary with the positions of the space) and unsteady (non-periodic or random) phe-

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nomena are one kind of the complex and intrinsic physical procedure which exist wide spread in the nature. With advancement of human being history, It has been the key for the breakthrough in science to understand the mentioned natural phenomenon as with many problems facing the fluid mechanics involved with complex and turbulent flows.

It is no way to solve the mentioned problems , like a blind man to touch an elephant, if the traditional approaches only used, which based on qualitative and steady flow visualization methods and techniques, even the great role have been taken to find the flow patterns and mechanism of the flows in the history [Roshko 1991], or which based on steady and single-point methods and techniques, even the great improvements have been made in systematization, minimization, increasing accuracy, precision and number of gathering data for the measurement.

As it is known, to emphasis on the research and development of an instrumentation, a non-intrusive and instantaneous technique and approaches, with not only high resolution in space and time but also whole volume and time history, was stated by American Physics Society 2000, NASA 2000 and NASA Aeronautics 21st century. Obviously it will be the most important target in the research front of the experimental fluid mechanics.

As everybody knows, it was only a dream for this kind of ideal experimental instrumentation if it was several ten years ago. But up to now, whichever approaches, the evolution of the flow visualization technique or flow parameter measurement technique has been taken place for several generations, and up to now it seems they come to get together and approach to the same stage, or could call, a result of the evolution, the 4th or 5th generation of the flow observation and measurement technique system, as shown in Fig.1.

High technologies, specially unbelievable great developing on computer technology, laser and modern optical technology, information, communication and digital image technology and etc. have made the attack on the fluid mechanics, such an ancient and important field. It is the time to be coming new generation of instrumental techniques for experimental fluid mechanics. With the interaction and permeability between the fields, it has the possibility to pursue and realize this ideal approach for the experimental fluid mechanics. Also it will be the challenge to us facing the 21st century.

In this paper we will briefly describe the target, so called“ ideal observation and measurement technique ”(IOMT) and the main approaches to the target, so called“ full flow field observation and measurement ”(FFFOM) technique. And as the most important and practical one of the main approaches, we will summarize and discuss the recent stage, progress and problems facing 21st century of particle image velocimetry (PIV).

1 On Ideal observation and measurement technique

Probably the most important target for the ideal experimental instrumentation and technique or say ideal observation and measurement technique (IOMT) is to be able to have breakthrough to understand the turbulence and complex flows. The author submitted the following further description

about the requirement of the performance & properties of IOMT [Shen1997].

(1) Non-intrusive, no or less interaction to the flows.

(2) Qualitative and quantitative investigation.

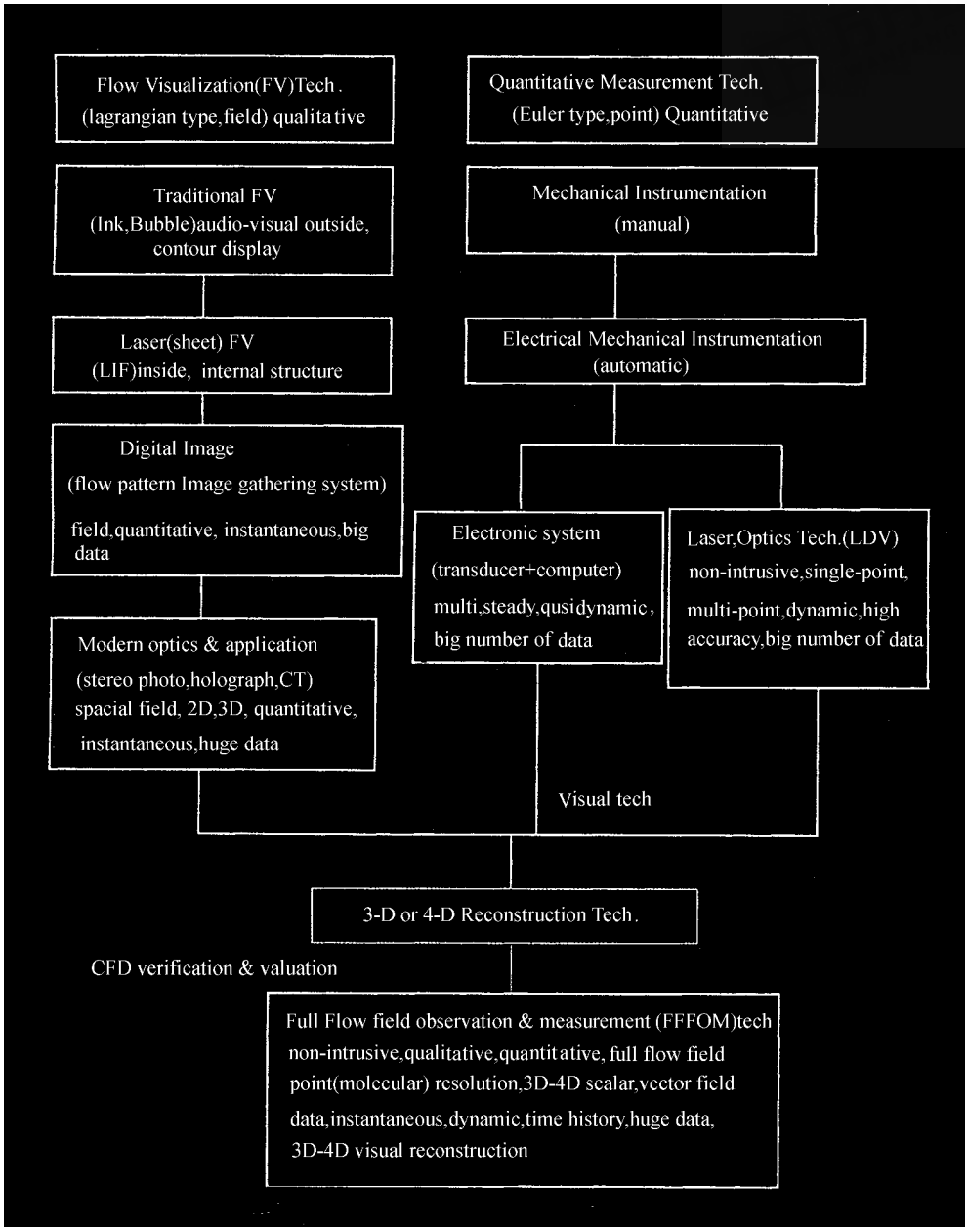


Fig.1　Historical revolutions of the observation & measurement tech. in fluid mechanics

图 1　流体力学中观测技术的变革历程

(3) Integrity and high resolution (spatial and temporal) of investigation.

The integrity here means to be able to observe the integrated whole space volume and time his-

tory or procedure of the evolution of the flows. It concerned mostly about the large structures and macroscopic evolution of the flows with full scales of space and time.

The high resolution here means to be able to observe the detail of the flows with high resolution in space and time scales. Or say, to observe the flows using macroscope with milliscope or microscope synchronously. It concerned mostly about the small or micro structures, procedures or evaluations of the flows and the connections of the different scalar structures of the flows.

Obviously, for the different research projects of the flows there are different scales of space and time. For example, the turbulent shear flow is one of the most important problems. For the mentioned requirement, to be able to observe the flow from large scale to micro scale synchronously as shown in Fig.2, that is including the large vortex structure scale $\lambda_\delta \sim \delta$; milli-scale or Taylor scale $\lambda_T \sim \delta Re^{-1/2}$; viscous scale or Kolmogrov scale $\lambda_\gamma \sim \delta Re^{-3/4}$; and molecular scale or Batchelor scale $\lambda_D \sim \delta Sc^{-1/2} Re^{-3/4}$. Also $\tau_\lambda = \lambda / Uc$ is the characteristic time scale, Uc is the characteristic conversion velocity. For the viscous time scale, may we could have $\tau_v = \lambda_v^2 / v$ and $\tau_v = \tau_\delta Re^{-1/2}$, here $\tau_\delta = \delta / u$ [Dahm 1985, Landohl 1986, Shen 1997b].

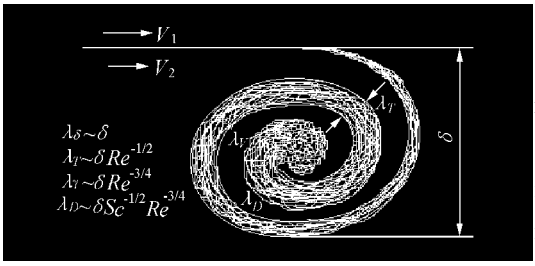


Fig.2 The spatial scales of shear flow
图 2 剪切流的空间尺度

The spatial scales in different levels and the requirements of the number account of the measuring meshes is estimated roughly in reference [Shen 1997b]. Also the table listed in mentioned reference probably the current high level of the mesh number account of CFD.

(4) High precision and accuracy.

(5) Audio-visual and perfect display results.

(6) On real-time or near real-time (at least on line).

(7) Low cost, friendly interface and good reliability.

The detail of the performances and requirements of the IOMT will not be discussed here [Shen 1997b]. Obviously they are very high and not easy to satisfy all of the requirements. But be sure, it will be able to approach to the target in the future, since so much progresses in this field have been achieved for recent decades.

2 On full flow field observation and measurement technique

Actually, many researchers have been working on to search and realize the approaches to the mentioned ideal technique and instrumentation for the progresses in the fluid mechanics for recent decades, and also many important achievements in this research field have been made up to now. As the author summarized and named, an approach so called "full flow field observation and measurement" (FFFOM) technique has been arising since the potential properties of this technique will be able to close to the ideal technique specially in not only qualitative, limited spatial and tem-

poral but also quantitative, full flow spatial and temporal performance. As a summary, the FFFOM systematic technique may be consisted of several main blocks as shown in Fig. 3. Perhaps we have to wait for the great progresses from many new high technology, including high spatial resolution and

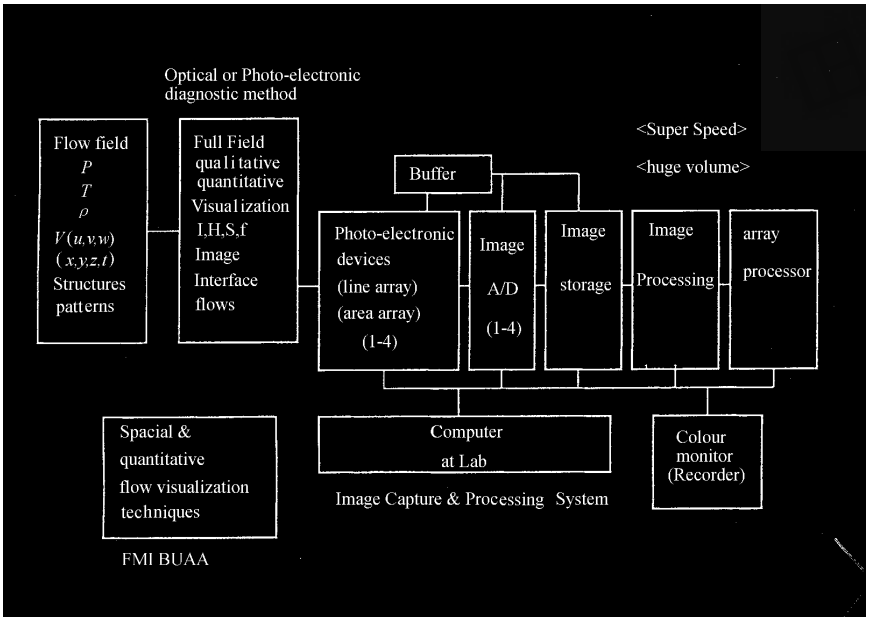


Fig. 3　Full flow field observation & measurement system

图 3　全流场观测系统

high frame rate CCD camera, super rate A/D converter, super rate of data transfer, huge data storage, super or parallel data processing speed hardware and their cost down for a moment. We have to concentrate to work on the first block of the system, that is the base of the whole technique to establish the diagnostic technique for flows using optical and optic-electron methods. That means the 4th or 5th generation of the experimental technique and instrument, which based on optical, optic-electron diagnostic methods and cored with modern image gathering and processing system or modern multi-medium system, is coming to us.

3 The trace and trend of FFFOM technique

Recent decades is the prominent period of time to have real progresses in the Full Flow Field Observation and Measurement technique. As shown in Fig. 4, the trace and trend of FFFOM are summarised briefly.

3.1　Laser spatial flow visualization

First as we know, it paid re-attention to the flow visualization since such many non-steady and complex flows facing to us and we know so less and have to understand the flows globally at first. With introducing many new techniques, specially the laser light sheet, laser beam scanning techniques, laser induced fluorescence (LIF) technique and etc., the flow visualization really has new faces which compared with the traditional ones. The flow structures and patterns could be able to ob-

serve and some new phenomenon have been discovered from integral level to more detail levels and from not only external contour view but also internal or sectional views [Shen 1989,1992]. They are the important technique bases for the FFFOM.

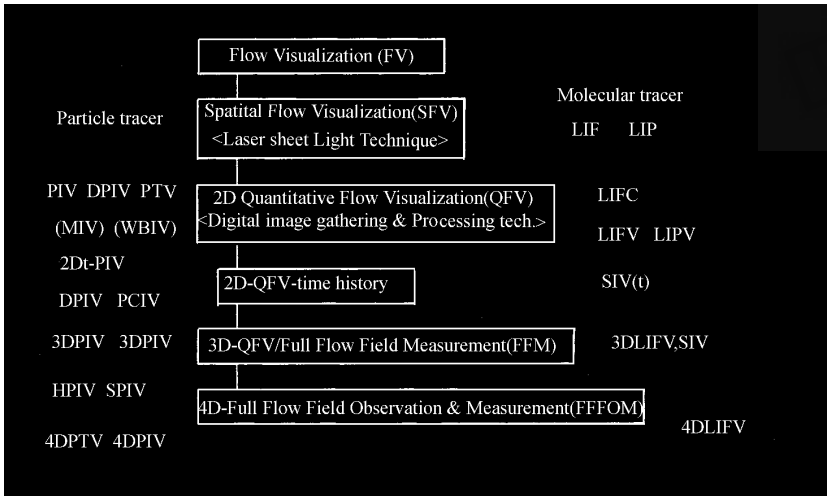


Fig.4 The trace & trend of the quantitative flow visuali zation the full flow field observation & measurement

图 4 定量流动显示/全流场观测的流程图

3.2 Digital image technology and quantitative flow visualization

Secondly, it is another important step to introduce the digital image gathering and processing system techniques to the fluid mechanics. It made the possibilities to observe the flows not only qualitatively but also quantitatively synchronously.

For examples, except LIF concentration field and velocity field measuring techniques using the molecular tracer, the particle image velocimetry (PIV) techniques using particles as tracers have been developed and applied in many cases of flow field since Prof. Adrian and etc. [Adrian 1986, 1991] had pioneer contribution to solve the key techniques. Also some commercial instruments of PIV (2D-2C) are valuable now. They all have quantitative performance using digital image system and have some main properties of the ideal techniques or so called FFFOM technique too.

3.3 3-D observation and measurement of the flow scalar or vector fields

Thirdly the three dimensional observation & measurement techniques with using stereoscope, multi-scope , holography or may tomography [Dracos 1995] techniques and etc. , have been introduced to the fluid mechanics. Here the three dimensions means the measurements at least with three components in flow velocity field, it could be in two dimensions in space or in three dimensions in space or in two dimensions in space with one dimension in time. As shown in Fig. 5 of the level techniques progress for optical measurement techniques, here 3C means three components of the flow velocity and 2D (x, y) or 3D (x, y, z) in space, or roughly say 3D including 2D (x, y) in space with t in time history, or more clear say separately 2D-3C, 3D-3C, $2D_t$-3C measurement technique levels.

Obviously the 3C scale field and 3C velocity vector field either in a section (x, y) of flows or

in whole volume (x, y, z) of flows all are the current research focus.

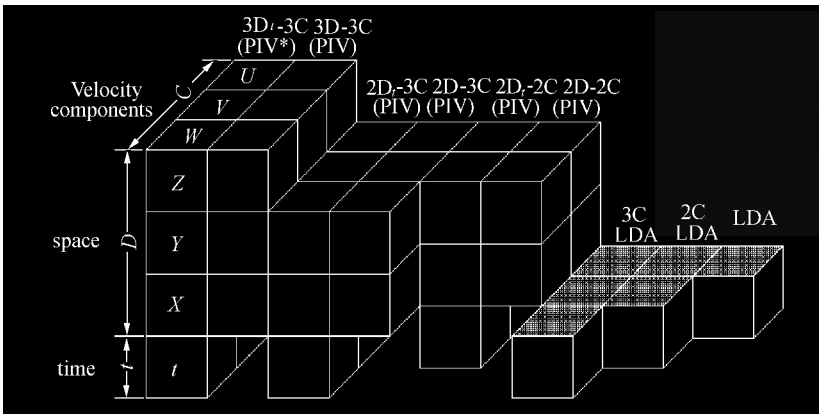


Fig.5　The level progress for optical measurement of flow velocity

图 5　光学速度测量技术水平进展

A couple of decades ago it seems it is impossible to be realized. But several techniques including 3D-3C PTV (particle tracing velocimetry using three or four cameras) [Sata 1992, Malik 1993], 2D$_t$-2C PIV (PICV particle image cinema velocimetry) [Ma 1993, Oakley 1994], 2D-3C PIV (SPIV stereo particle image velocimetry using twin cameras) [Prasad 1993, 1995, Shen 1995], and 3D-3C PIV (HPIV holograph particle image velocimetry using double exposure holographs) [Meng1991, Scherer1993, Barnhat1994, Shen1998], all were already realized during the latest decade.

Also as using molecular tracer, the 2D-2C or 3D-2C SIV (scalar imaging velocimetry) [Dahm1992] and ICV (image correlation velocimetry) [Tokamaru1992] have been researched. They are all quite close to the target too.

3.4　4-D observation and measurement of the flow scalar or vector fields

The Fig.4 and Fig.5 also showed the trend of the FFFOM technique. Here 4D-four dimensional observation & measurement means three dimensions in space with one dimension in time history, i.e., 3D$_t$-3C. We will attend to continue attack to 3D$_t$-3C observation and measurement target, the three components velocity vector field measurements in the full flow field with full time history, in near future. Be sure, a breakthrough progress and a new generation of the observation and measurement technique and system in the fluid mechanics will be coming across 21st century.

4　Some discussion on PIV

4.1　The progress and recent stage of 2D-PIV

As the most important and practical one of the FFFOM techniques, the Particle Image Velocimetry (PIV), as named using particles as tracers in the fluids as comparison with using molecule as tracers, has great progresses, especially for 2D-PIV techniques, not only for the key techniques but also the application to various flows.

As we know, PIV (Particle Image Velocimetry) has been studied and developed for years since

1970. According to the key or main problems for PIV, the several important steps (or say high light) of the progress of PIV were evaluated as following.

At first the automatic interrogation system using optical Young fringe method for the PIV film, which was solved one of the main techniques to make the possibility to deal automatically with the huge image data of the particle displacements, was realized by Adrian first and others in 1986-89 [Adrian1986,1991, Liu1991]. It is a very important step for PIV even the Younge method may not used now anymore mostly.

Secondly, after testing using single laser and finding the limitation of performance for recent single laser, a twin laser system (mostly using YAG laser, 10 ~ 30 Hz), which illuminated the flow field with two light sheet pulses and can be used for wide range of flow velocities (from several mm/s to 1000 m/s) with high accuracy of the time interval (ns), was designed and provided in 1989-1991.

Thirdly for the PIV recording, after the film camera (35mm, 60mm) and general CCD camera (512×512, 480×720), in which the spatial resolution had roughly 3500 ~ 12500 and 500 ~ 6000 vectors / frame, with various shifting devices were used mostly, now a new CCD camera system, a twin frames recording system, has been developing to practical using since the developing of several generations of CCD camera systems (including a twin CCD camera system with a 50/50 view splitter like a twin laser system in pricinple [Willert 1995]). The new camera system which was called the cross-frame CCD camera has following performances:

· With using the cross-frame technique which can capture the pairs of images with deferent time interval between the pair of images (from 200ns or 2μs to 1s, it almost matched with the velocity range of the recent twin laser system).

· With time history recording (5 ~ 15 pair frames per second).

· With the on-line measurement of the velocity vector field using the cross-correlation function data proceeding without using any shifting devices.

Finally with mentioned progresses, some special techniques have been developed too.

(1) The seeding generators with deferent seeding techniques (using heating techniques or air-operated techniques) have developed for practical using in the wind tunnel (mostly using $d_p = 0.5 \sim 1\mu$m oil particles) and water channel (using various kind of particles).

(2) The image shifting techniques (using mechanical devices or imaging shifting) can be applied in the various flow cases, especially for the uniformity measurements of velocity field in the wind tunnels or water tunnels, even using the cross-frame CCD camera system [Reffel 1995, Shen 1997b].

(3) The software for processing the PIV image records have developed with quite fast response time (developed from several ms/ vector to several μs/ vector based on PC computer), may recently including using some new techniques like the parallel calculation, the neural networks or the optical flow analysis [Quenot1998], and with quite accepted good accuracy (1% mostly and up to 0.1% ~ 0.5%), using subpixel fiting techniques.

On the other hand, using PIV even the spatial and temporal resolution of the recent level of PIV was not enough mostly to investigate the small structures of the turbulent flows, the application testing research have been done and the instantaneous structures were investigated in various flow fields (specially the vortex flows or a turbulent flows in low *Re* number) with from the small size research laboratories to the aerodynamic industry facilities as following typical examples:

· Investigation of the properties and structures of a starting vortex flow passed through a backward facing step using a special PIV technique without using laser system, so called "white light bubble image velocimetry" (WBIV) [Shen 1996].

· Instantaneous velocity field measurement for the separated vortex flow from leading edge of a delta wing with high attack of angle in the wind tunnel [Kompenhans 1996] or with the periodic pitching oscillating in the water channel [Ma 1997].

· Instantaneous velocity field measurement for the free jet flows with the main flow speed from 15 m/s to $M = 1.5 \sim 2.5$.

· Instantaneous velocity field measurements for the Benard-Marangoni convection flow [Kong 1996].

· Instantaneous structure visualisation and velocity field measurement using SPIV for the turbulent boundary layer flows [Liu 1996].

· Instantaneous investigation and velocity field measurement for the turbulent channel flows [Adrian 1997].

· Some examples using in big facilities: [Willert 1997].

* Instantaneous velocity field measurement of the tip vortex flow for the helicopter in PWTH Aachen.

* Instantaneous velocity field measurement of the wake flows for a lifting wing (half model) in the 6m × 6m wind tunnel of DNW.

* Instantaneous velocity field measurement testing of the separated vortex flow from the leading edge of an aircraft model in the 6m × 6m wind tunnel of DNW recently.

* PIV with special designed light sheet delivery, seeding and image acquisition system to measure the velocity field of the blade in the turbomachinery in NASA Lewis Research Centre [Wernet 1997].

Most results of mentioned measurements showed that it makes really difference with the conventional flow visualization and measurement techniques which based on single point or steady and local measurement and missed the flow structures in the many cases of the unsteady flows (specially the instantaneous velocity field compares with the average velocity field).

Also some special techniques have been developed for the mentioned industry application including:

* synchronization control of two to four twin laser systems for illuminating large view area.

* the large scale optical mechanical set-up system.

* the remote focusing control for the CCD cameras.

* the remote control for the seeding flux rate.

* the remote control for the triggering laser light pulses.

* the software of 2D-PIV data processing, which had a quite fast response time and quite good accuracy with quite nice friendly interface for the high efficiency, safety and easy to using that industry needed .

4.2 Some progress of SPIV

For the instantaneous 3-component velocity field measurement in a section view (x, y) of flows, except the 3-hole mask lens and some special optical arrangement techniques, the three kinds of the Stereoscopic Particle Image Velocimetry (SPIV) methods have been studied.

(1) The first one had a special arrangement of the lens and film planes of the twin cameras (not coordinated axis) by Adrian 's group [Prasad 1993].

(2) The one had the optical arrangement of the positions of the object flow section, lens and the image plans of the twin cameras with the translation function to have the same magnification for the whole view field, and had applied to investigate a 3-D vortex water flow passed a diagonal cubic box [Shen 1995]. Also it had the same optical arrangement but using the twin CCD cameras which had some performance of time history recording (5 Hz) and applied to turbulent boundary layer flow [Liu 1996, Adrian1997].

(3) The another one had the optical arrangement with so called the hybrid method (a combination of translation and angular adjustment with Scheimflug criterion function) to have some advantages with lower illumination needed and to need a special calibration for the difference of magnification, and had applied to a starting jet flow [Prasad1995, Gaydon 1997].

As mentioned, all kinds of the optical arrangements for SPIV can not use normal camera usually and need some special cameras which could adjust the positions and direction of the lens and recording plan. We still need to continue to work on the improvement of this SPIV techniques for the practical application to the various flows and different testing facilities.

4.3 Some progress of HPIV

For the instantaneous 3-component velocity field measurement in a 3-D volume (x, y, z) of flows, the holograph particle image velocimetry (HPIV) technique as one main approach recently has been studying.

As the pioneer work to apply holograph to PIV, typically the two perpendicular directional on-axis holographs and two-component particle displacement image capture method were used for a small flow testing section by Hussain 's group and also some others had issues since 1990s [Meng 1991, Scherer 1991].

For the quite high resolution, typically the holograph in which the optical arrangement had the phase conjugate, off-axis with two directional object and reference lights, and the stereoscopic particle image capture method were used for a channel flow by Adrian 's group [Barnhart 1994], and also others did some work on off-axis holographic arrangements.

Recently for the high resolution, typically the so called hybrid holographic PIV method, in

which the two perpendicular directional off-axis holographic arrangement and two-component particle image capture method were used, was provided for a square duct by Katz's group [Zhang 1997].

We did some work on the off-axis, diffusible holographic optical arrangement without ambiguity of velocity direction, in which particularly the two reference lights come separately from the different directions and different light pulses when reconstruction of hologram, the stereoscopic particle image capture method and cross-correlation method in HPIV to investigate a 3-D vortex water flow passed a diagonal cubic box [Shen 1998,1999].

Up to now, the HPIV techniques are still very complicated, need too much procedures, not easy to get fine hologram without very high quality and power of laser light, not easy to be reconstructed without distortion, not easy to match the pair of recording images without calibration, and need off-line data processing and so on. Also now there is no time history recording mostly.

4.4 Some discussion of further work on PIV

As the recent stage of PIV, even $2D_t$-2C PIV, the spatial and temporal resolution is still limited. For the 1024×1024 cross-frame CCD camera (5 ~ 15 frame pairs per second) it can mostly applied to the investigation of the large scale structures of the flows. But obviously it is not enough to apply to the investigation of the small structures and the evolution of the structures of the flows. Specially for the turbulent flows it is required not only very high spatial resolution but also very high temporal resolution.

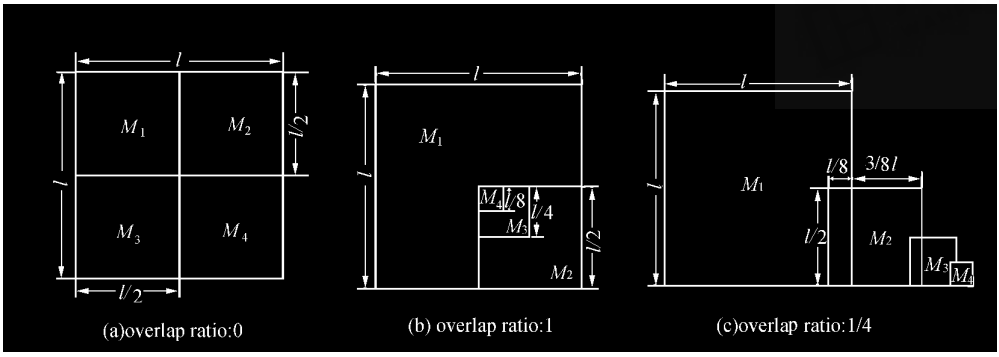
We need continue to work on the advance techniques research of 2D-PIV for the improvements of the spatial and temporal resolution:

For wide range of velocity measurement, the CCD camera needs to have less the time interval between the shutters of the pair images which could match the velocity range of the recent twin YAG laser system (20 ~ 200ns);

For the high spatial resolution, with pixels more than 4096×4096, higher spatial resolution CCD camera is required. Even still work on using large width film 70 ~ 100 mm moving cameras with the special shifting and using a laser digital scanner with the maximum width 100mm and resolution 2000 dpi for the higher spatial resolution comparison with using CCD cameras recently [Adrian1996]. For the investigating viscous structures with large structures of a turbulent flow as according to estimate roughly [Shen1997b] for an example, $\lambda_v/\lambda_\delta \approx 0.925 \times 10^{-3}$ only in $Re = 1.1 \times 10^4$, may the spatial resolution of 1000×1000 vectors/ frame be needed. Also some other techniques will be useful like as the interrogating process with more overlapping spot and coming to tracking each particles and as a multi-camera arrangement with strategies using the same or different magnifications for particular testing as shown in Fig.6.

For the high temporal resolution, it needs not only high frame pair rate of CCD camera but also high repeat rate of the twin laser system with high power of pulses. For examples as according to estimate roughly as the formulas [Landahl 1986], the viscous time scale τ_v is 1.14ms for the investigation of a turbulent flow in a backward facing step water flow with 100mm step height at velocity of 120 mm/s ($Re = 1.1 \times 10^4$), and the τ_v is 0.87μs for in a wing chord of 5m flying at velocity of

100m/s ($Re \approx 3.3 \times 10^7$), so it is required not only the rate of CCD camera at least 1000 to 10^6 frame pairs per second but also the high frequency illuminated systems (for example a twin laser system with 1000 to 10^6Hz rate even more or to discover some new light sources) to match each other even for the $2D_t$-PIV.



view area : $l \times l$ M_i-view area of Camera

(a) $M_1 = M_2 = M_3 = M_4 (\sim l/2)$ (b) $M_1 = 2M_2 = 4M_3 = 8M_4 (M_1 \sim l)$ (c) $M_1 = 2M_2 = 4M_3 = 8M_4 (M_1 \sim l)$

Fig.6 Strategies arrangements of multi – camera with different magnification for higher spatial resolution

图 6 为有较高分辨率,不同放大率的多台相机的组合安排

On the other hand we need continue to work on the investigation of the various flows for the application of PIV in the high speed (specially supersonic) flows, except to need high frame rate camera, we need find and test some particles which follow the supersonic flows definitely or using something like PHANTOMM as tracers [Harries 1996,1997]. May which could still call PIV, but here the phrase of P means PHANTOMM.

Another very important direction for $2D_t$-PIV recently, the $2D_t$-PIV application for the industrial and commercial use, specially for the large scale fluid testing facilities, may will be taken more attention. We need continue to work on the applications of PIV in the large scale wind tunnel (2.5m × 3m or more) and the large scale water tunnel or channel (1m × 1.2m or more) for the industry, for which it required specially the real-time data processing and very high efficient interface performances. The benefits of using PIV in the large scale facilities not only have the new performances of the instantaneous full field measurements but also have the high efficiency and low cost for the facility running.

For the 3C-PIV as mentioned before, whichever the 3-component velocity field in a sectional view or the 3-component velocity field in a volume, there are a lot work to have to do especially for the industrial and commercial application.

Certainly we need attend to continue attack to 4D observation and measurement target (3-component velocity field in a section, $2D_t$-3C PIV and 3-component velocity field in a volume with time history, $3D_t$-3C PIV) for the flows investigated with full field and full time history. May so called "HMPIV "(holographic movie PIV) will be a way to the target.

Obviously all of mentioned fields will be the challenge to us facing the 21st century.

5 Some remarks

As mentioned as a new generation of technique and instrumentation which will be across the new century, the full flow field observation and measurement (FFFOM) technique system, an ideal or near ideal experimental observation and measurement technique (IOMT), will be sure to realize for the fluid mechanics.

Also obviously the PIV technique not only is one of the approaches to the ideal observation and measurement technique but also is the mainly powerful, most practical and promising potential approach to facing the 21st century. It is great fortune for us we have already been working on this promising field and had important contribution in this open field for years.

Based on the mentioned progresses, it showed that up to now the great time is coming to the PIV techniques since the basic technology of PIV, specially for $2D_t$-PIV, not only has solved mainly and was already practical to use for the basic research of the fluid mechanics, but also is coming to the standard stage for the industry and commercial application. Be sure, with all reseachers' works on this field in the world, it seems that it will be like a revolution of the observation and measurement technique system for the fluid mechanics and will be quite popular to use in both research and industry laboratories in the near future.

Permeating and blending with the new high technology, specially the unbelievable great developing on computer technology, laser and modern optical technology, information, communication and digital image technology etc., and with the numerical simulation approach (CFD), be sure, a breakthrough progress and a new generation of the observation and measurement technique and system in the fluid mechanics will coming around across the new 21st century. It will provide the promising approach to observe, measure, understand and discover the structure and mechanism of the complex and turbulent flows. The great time to have the main solution of the complex and turbulent flows, the great developing time for the fluid mechanics will be sure to come in the near future. Also it will be the challenge to us facing the 21st century.

Also it confirmed that all of our works was no doubt to have the important contribution for these high lights.

Due to the limitation of the full-length paper and my aspect range observed, some important works and contributions in this field may have not shown here, may I have a sincere apology for them.

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