GRADUATE AERONAUTICAL LABORATORIES
CALIFORNIA INSTITUTE OF TECHNOLOGY

DE-FOCUSING DIGITAL PARTICLE IMAGE VELOCIMETRY SYSTEM

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Annual Performance Report
9/1/01 – 8/31/02

AFOSR Grant F49620-01-1-0207

Prepared for
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REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-03-0227

1. REPORT DATE *(DD-MM-YYYY)*: May 14, 2003

2. REPORT TYPE: Annual Performance Report

3. DATES COVERED *(From - To)*: 9/1/01 to 8/31/02

4. TITLE AND SUBTITLE

De- Focusing Digital Particle Image Velocimetry System

5a. CONTRACT NUMBER

5b. GRANT NUMBER: F49620-01-1-0207

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR (S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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1200 E. California Blvd.
Pasadena, CA 91125, USA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFORS/PK4
USAF,AFRL
AF OFFICE OF SCIENTIFIC RESEARCH
801 N. Randolph Street Room 732
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The work under a Grant from DURIP is to build and test a velocimetry system in support of an AFOSR Grant for making three-dimensional, three-component velocity field measurements in supersonic transverse jet injection in the Caltech Ludwieg Tube.

All of the components of the system have been purchased, and those that needed to be manufactured in the machine shop have been designed and built. Improvements in hardware, recognized during the design and construction, both from practical points of view and from the point of view of comparison of data with computation, have led to changes in design. These were implemented, but require extensive new software that is being generated prior to the calibration of the system.

15. SUBJECT TERMS

Three-dimensional, three-component, particle-tracking, velocimetry

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Hans G. Hornung
Unclassified	Unclassified	Unclassified	UL	6	19b. TELEPHONE NUMBER *(include area code)* (626) 395-4551

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1 INTRODUCTION

This report presents a description of the work performed under the DURIP grant to build a defocusing digital particle–image velocimetry (DDPIV) system, for initial use in an ongoing project supported by the AFOSR (Dr. Steven Walker). DDPIV is a technique that had been developed at GALCIT by Professor Gharib's research group for instantaneous measurement of three-dimensional, three–component velocity fields. The work supported by AFOSR has the aim to obtain detailed velocity fields of the flow resulting from supersonic transverse jet injection into a supersonic cross flow in GALCIT's supersonic Ludwieg tube facility (LT). In particular, the goal is to obtain good data sets over a large parameter space for testing computational methods. DDPIV is state–of–the–art in Particle Imaging Velocimetry, and has been demonstrated to yield results with good spatial resolution and accuracy. The system will also be used in a graduate–level class on experimental methods, and future projects to be conducted in the LT.

In the following, the statement of work, the details of the instrument and the progress to date are presented.

2 ORIGINAL STATEMENT OF WORK

1. Design and construct the DDPIV system, purchase and construction of triple camera, purchase and assembly of CPU and frame grabbers, installation of acquisition software.

2. Test and calibrate the complete system, shake down and find limits of spatial resolution and flow parameter ranges.

3 PURPOSE OF THE PROJECT

A new supersonic wind tunnel using the Ludwieg Tube principle was completed in 2000 at the Graduate Aeronautical Laboratories at Caltech. The facility is designed to operate at Mach numbers from low supersonic to 4, and Reynolds numbers based on the square root of the test–section cross–sectional area up to 20×10^6. The first nozzle is designed for $M_\infty = 2.3$, the approximate maximum Mach number for steady flight with conventional materials. The test section in this rectangular nozzle has a cross–section of 200×200 mm. A special feature of the facility is that the boundary layer forming on the walls of the tube is sucked off through an annular throat just upstream of the contracting part of the nozzle, in order to maintain good flow quality throughout the run duration of approximately 100 ms. Good flow quality and short run duration are the two features of the Ludwieg Tube principle that make it attractive and affordable. The Ludwieg Tube laboratory has been funded by a donation from the John and Anna Wild estate.

In the late 1990's Professor Mory Gharib and his group at GALCIT have developed the new technique of Defocussing Digital Particle Imaging Velocimetry (DDPIV). A DDPIV system uses three double–exposure imaging systems that permit the measurement of the instantaneous velocity field of a flow, providing three–component information on a three–dimensional grid. Such information is extremely interesting, because it provides *simultaneous* velocity field information, rather than time–separated information on planes, as is typical of conventional PIV (two–components), or even Stereo PIV (three components). Furthermore, it dovetails very well with the Ludwieg Tube operation, in which conventional PIV would require some 20 runs to provide three–dimensional information, whereas DDPIV provides the same in a single run. For example, with 10 runs per day, DDPIV could provide 10 complete, time–correlated flow fields in the time it would take to obtain one by conventional methods. Two such systems have been constructed by the Gharib team, and they have developed considerable experience in its design, construction and calibration.

A project supported by the AFOSR (originally Dr. Steven Walker, now Dr. John Schmisseur) aims to use DDPIV in the Ludwieg Tube for the study of supersonic transverse jet injection into supersonic cross flow. This is a flow type that is interesting for a number of different applications, in two main categories: One is to mix fuel into a supersonic air stream for supersonic–combustion ram jet propulsion, where the emphasis is on quality of mixing. The other is to cause a reaction force on a vehicle traveling at supersonic speed, or in a supersonic nozzle for thrust–vector control, where the emphasis is on effectiveness and undetectability of vehicle control. In both cases good design depends crucially on the capability to compute, and thus to predict, the associated complex turbulent flow field. Such flows are also of interest to the ARO (Dr. David Mann). The AFOSR project aims to use the extreme productivity of the approach to explore cost–effectively the parameter space of this problem with sufficient spatial resolution to provide computational fluid dynamicists with good data for evaluation and comparison of different turbulence models or LES techniques in this highly complex but important flow type.

While the DDPIV system is initially being constructed to support the AFOSR project, its useful life time, with minor maintenance, is at least 12 years. This is considerably longer than the duration of the work planned in that proposal, so that the instrumentation system would continue to be used in the supersonic LT for other research projects as well as in graduate laboratory-class projects.

The combination of the Ludwieg Tube and the DDPIV instrumentation will enhance the research capability of GALCIT substantially in experimental dynamics of supersonic flow. Ph. D. graduates who have state–of–the–art, hands–on experience in this area will continue to be needed by the defense industry.

4 PRINCIPLE OF DEFOCUSING DIGITAL PARTICLE–IMAGING VELOCIMETRY (DDPIV)

Fig. 1 (top) shows a schematic of an imaging system with a single aperture at the center of the lens. Object A on the reference plane is focused in a sharp image on the image plane. Object B, closer to the lens than the reference plane, forms a blurred image on the image plane, as shown in the black images on the left. If instead, a mask is used that has two apertures, at equal distances from the lens axis, as shown in Fig. 1 (bottom), an object B that is closer to the lens than the reference plane is imaged at B", so that it forms two blurred images B'_1 and B'_2 on the image plane. The separation distance of these images is a measure of the distance between B and the reference plane. With two apertures, there are, however, two positions that produce exactly the same image separation distance. One of these is closer to and one further from the lens than the reference plane.

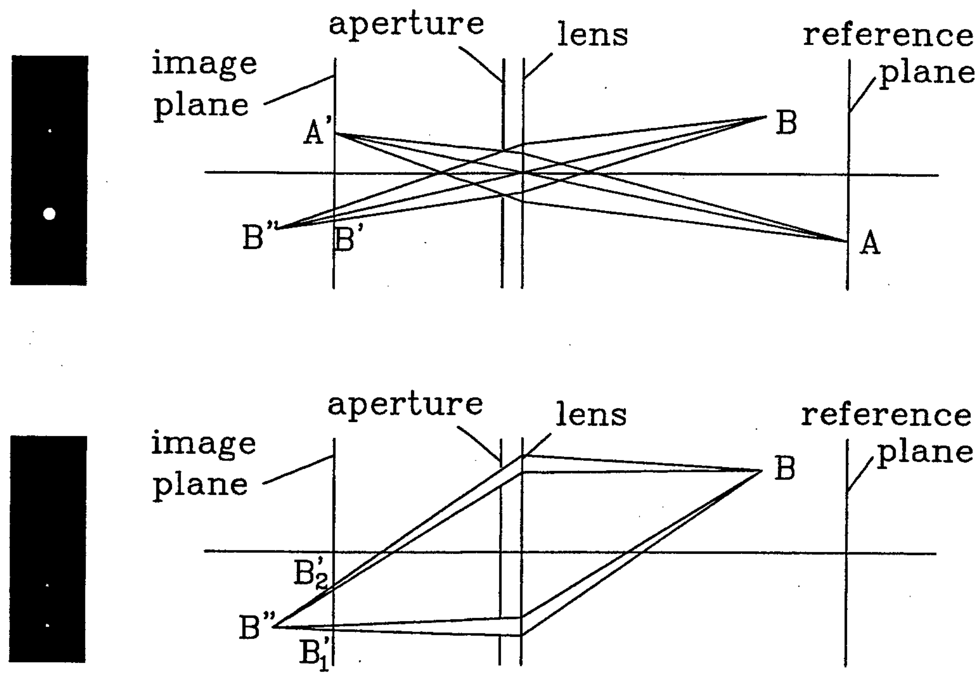

Figure 1. TOP: Schematic sketch of an imaging system with one central aperture. BOTTOM: System with two off–axis apertures.

A system with three apertures, as shown in the perspective sketch of Fig. 2, eliminates this ambiguity. Object A, in front of the reference plane, forms three images on the image plane that are at the apexes of an upright equilateral triangle, while object B, behind the reference plane, forms an inverted triangle image. A precise relation may be derived between the size of the triangle and the distance of the object from the reference plane, for a given geometry and magnification of the optical system. The larger the separation of the apertures, the smaller will be the error of the depth location.

A DDPIV system with a three–image scheme has been developed by Pereira, Gharib, Dabiri and Modarress (2000), in which large separation of the three apertures was achieved by using three accurately located, separate cameras to form three separate CCD images, that were then superimposed digitally with accurate relative location. The resulting image then forms upright or inverted triangular images of each particle.

In velocimetry, two such images are recorded, separated in time by a small laser–pulse interval. The processing steps of the data are as follows: First, the intensity of each particle image is fitted by a two–dimensional Gaussian surface. The standard deviation, centroid, and amplitude of each Gaussian are optimized by a least–squares fit. Second, a search is done to identify triplets of fitted particle images that form equilateral triangles. The size and centroid location of any completed triangle determines the coordinates of the particle. Third, the displacement of each particle during the laser–pulse interval is determined by a three–dimensional cross–correlation of voxels from two sequential DDPIV data sets. The interrogation voxel is marched through the whole volume. The computed displacement

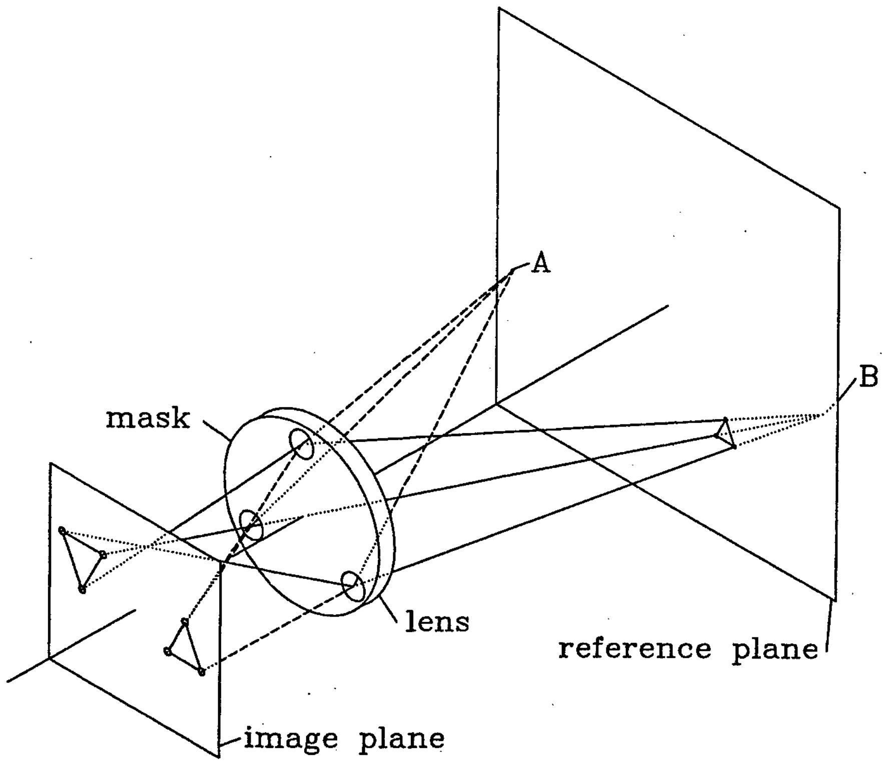

Figure 2. Perspective sketch of a three–aperture imaging system. Object A, in front of the reference plane makes three images forming an upright triangle, while object B, behind the reference plane, forms an inverted triangle set.

vectors together with the laser–pulse time interval then give the three–dimensional three–component velocity field.

Pereira *et al.* (2000) calibrated their system by moving a dot pattern drawn onto a glass screen with a translation stage to determine the location error, and by spinning a dot pattern drawn onto a disk oriented at different directions to determine the velocity error. In a measuring volume of $300 \times 300 \times 300$ mm the transverse location error was found to be $\pm 50\ \mu$m while the depth location error was $\pm 650\ \mu$m. The velocity error was ± 2.5 %. These errors scale approximately with the length scale of the measuring volume. Pereira *et al.* have applied this method, *e. g.*, to the measurement of the flow field in the wake of a propeller in water, where they obtained three–component velocity vector fields on a three–dimensional grid at a frequency of 16 Hz.

5 PROGRESS TO DATE

The progress in the construction of the system has been slowed down because a number of improvements in the design of the hardware became apparent, and we wanted to take advantage of them. i

The mounting of the CCD cameras on translation stages proved to be too flexible to provide the accuracy of locating the particles that was desired. It was therefore decided to mount them directly on the mounting plate, and to account for their exact location by the calibration software and procedure. This required new software to be generated for this purpose.

Some of the adjustments of the cameras were internal to the cameras, so that they had to be dismounted in order to be adjusted. Clearly, this is not very satisfactory, firstly because it is very time-consuming, and secondly, because it would require the calibration procedure to be repeated each time a camera needs to have an adjustment made. The cameras were therefore modified to bring the adjustment screws to the outside, thus enabling adjustment without dismounting.

It was recognized that the measuring volume did not need to be as large as had been originally intended (150×150 × 50 mm), and that 50×50×50 mm would be sufficient. This allows the laser beam to be concentrated into a smaller area, and therefore provides stronger scattered particle images. This is of considerable importance, since it was also decided that smaller particles would be needed to get the spacial resolution of shock waves that is desired. The camera placement therefore also had to be modified.

Discussions with numerical analysts suggested that it would be desirable to get as large a number of velocity vectors as possible for meaningful comparisons of LES computations with the results. It was therefore decided to change the scheme to a particle tracking system, in which the vectors provided by individual particles are used directly rather than making moving averages of vectors. With suitable new software it was estimated that 10,000 vectors should be achievable in each realization. This will require extensive new software to be generated. during the next months.

All the components of the system have been purchased, and the construction of the system in its new configuration is complete.

6 CONCLUDING REMARKS

Delays caused by redesign to improve the system have caused us to have to ask for extensions of the project. However the improvements will provide very significant enhancement of the volume and quality of the data. It does require generation of extensive new software, the generation of which is the main remaining task before calibration and implementation of the system.

7 REFERENCES

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