AIAA 2003-0920

Real-Time Particle Image Velocimetry for Closed-Loop Flow Control Studies

Stefan Siegel*, Kelly Cohen**, Thomas E. McLaughlin†
Department of Aeronautics
US Air Force Academy, CO 80840-6222

James Myatt‡
Air Force Research Laboratory / Air Vehicles Directorate, Wright-Patterson AFB

Abstract

In order to facilitate closed loop feedback control research in water tunnel experiments, a sensing system capable of providing non-intrusive real time velocity information at multiple locations in the flow field was needed. In order to meet these demands, a real-time capable particle image velocimeter was found to be the most advantageous solution. Since no commercial system is currently available to meet these application requirements, this system has been developed from scratch.

The system uses a commercially available off the shelf camera, laser and data acquisition components along with custom software. The performance of the system in terms of velocity measurement accuracy is equivalent to commercial systems. The time delay for processing the image information is in the order of 0.44 ms per vector, plus the transfer times for both data and images. The overall time delay for a typical setup where 6 interrogation areas will be correlated in real time is in the order of 70 ms. This compares to fundamental frequencies encountered in water tunnel experiments that are on the order of 1 Hz, resulting in a time delay of about 7 percent of a shedding cycle. For a moderately robust control algorithm this value is very acceptable.

Introduction

Although there has been intense research in aerodynamic flow control, full implementation of the active manipulation of a flow field has remained elusive. However, with the surge of new technologies in the areas of sensors, actuators, real-time data processing, and nonlinear feedback control, the dawn of the "closed-loop era" is breaking. The necessary pieces exist; assembling them together effectively is the current challenge. This area of research is multi-disciplinary in nature, merging the fields of fluid mechanics, controls, simulations, real time data processing, structures, sensing and actuation.

Due to its canonical nature, the phenomenon of vortex shedding behind bluff bodies has been a subject of extensive research. Many flows of engineering interest produce the phenomenon of vortex shedding and the associated chaotic response. Applications include aircraft and missile aerodynamics, marine structures, underwater acoustics, and civil and wind engineering. The ability to control the wake of a bluff body could be used to reduce drag, increase mixing and heat transfer, and enhance combustion.

Flows with absolute instabilities behind bluff bodies, an archetype of which is the cylinder wake, demonstrate self-excited oscillations even when all sources of noise are removed[4]. Above a critical Reynolds number (Re ~ 47), non-dimensionalized with respect to freestream

---

* Visiting Researcher,Member

** Visiting Researcher, Member

† Research Contractor, Associate Fellow

‡ Aerospace Engineer, Senior Member

speed and cylinder diameter, a significant region of local absolute instability occurs in the wake of a two-dimensional (2D) cylinder. This results in global flow instability, also known as the von Karman vortex street. At the U.S. Air Force Academy, current research efforts are under way to experimentally examine closed loop flow control strategies for the above mentioned flow field. For this system, a control strategy is based on real-time multi-sensor information obtained from a Particle Image Velocimetry (PIV) system.

Particle Image Velocimetry (PIV) has developed into one of the most powerful experimental measurement techniques available for detailed flow diagnostics in recent years. Its main advantages are the ability to measure an entire cross section of a flow field at once and obtain two or even three dimensional velocity vector information. The recent advances in processing capabilities of modern personal computers enabled researchers to utilize the large amounts of data gathered during PIV measurements, thus allowing much greater insight into complex flow fields than previously possible.

Currently, several companies offer PIV systems comprising both the hardware and software necessary to conduct off-line measurements. Use of these systems requires several discrete steps involving image acquisition, image correlation and data post processing to obtain flow field information. Other than acquisition, all of these steps can only be performed off-line; no real-time flow field information is available. This paper describes the development and performance of a unique, real-time capable PIV system developed at the U.S. Air Force Academy. This system seeks to adapt PIV for use as a feedback control sensor, performing all of the above functions in a time frame suitable to control problems.

Development Objective and Uniqueness of Approach

For an experiment involving closed-loop feedback flow control of a von Karman vortex street behind a circular cylinder, real time flow field information is needed at several locations in the wake downstream of the cylinder. This experiment is to be conducted in a low speed water tunnel in order to achieve the required Reynolds number, as well as a low vortex shedding frequency. Target parameters are a Reynolds number of 120, at which vortices will shed at a frequency of 1.2 Hz. In order to obtain enough instantaneous information on the flow field, multiple sensor locations in the wake must be simultaneously monitored. Additionally, the flow field features an absolute instability downstream of the cylinder. This wake region is extremely sensitive to intrusion by sensors; at this Reynolds number, discrete pressure or velocity sensors in the wake would certainly corrupt the flow. Therefore non-intrusiveness of the sensors is an important requirement since the wake region provides the most valuable flow field information.

Evaluation of the currently available sensing options is shown in the next section, followed by a description of the real-time particle image velocimeter system developed in order to meet the sensing needs of this experiment. A comparison to commercial off-the-shelf (COTS) PIV systems follows.

Review of Currently Available Sensors

To meet the sensing requirements, several currently available sensing systems were evaluated for suitability. The low speed water tunnel environment ruled out pressure based methods a priori, due to the unavailability of sensors with sufficient resolution. All other possible options are discussed in the following sections.

Hot Film Probes

Hot film probes are a well-proven technique for measuring velocities in a water tunnel. The inherent advantages and disadvantages of hot film probes for the task at hand are listed in Table 1. The main disadvantage of Hot Film Probes is their intrusiveness, ruling out their use for measurements in the near wake of the cylinder.

Laser Doppler Anemometry

Laser Doppler anemometry (LDA) is as well established as is the use of hot film probes. The inherent advantages and disadvantages of LDA for the task at hand are also listed in Table 1. Unlike hot film probes, however, LDA is a non-intrusive measurement technique and is therefore feasible for use in the absolute instability region of the wake. However, an LDA system only provides a single sensor location in the flow field, which is not sufficient for the current project. Multiple LDA systems could be used to perform the job, but are prohibitively expensive for the current work.

Particle Image Velocimetry

As Table 1 shows, a PIV system fulfills all the requirements for this project. The only two drawbacks are limited time resolution and the unavailability of a commercial system that is capable of producing measurement signals in real time. The time resolution of most PIV systems is limited by the interface between

System Criteria	Hot Film Probe	Laser Doppler Anemometer	Particle Image Velocimetry
Intrusiveness	Intrusive	Non-Intrusive	Non-Intrusive
Availability	Commercially Available	Commercially Available	Not Commercial Available for Real Time Use
Price	Relatively Inexpensive	Very Expensive	Moderately Expensive
Real-Time Capability	Yes	Yes	Not Commercially Available
Separate Velocity Components	Only Combination of U and V (Magnitude)	Up to 3 Independent Velocity Components	Up to 3 Independent Velocity Components
Frequency Response	Excellent	Good	Limited by Camera / Laser
Ease of Calibration and Positioning	Difficult to Calibrate in Water	No Calibration necessary	Easy to Calibrate
Multi Sensor Capable	One Sensor Location per Probe	One Sensor Location per Unit	Numerous sensor Locations

Table 1.Comparison of sensing system advantages and disadvantages

the camera and the frame grabber card, and the camera frame rate. State of the art systems have a data throughput of up to 50 megabytes/s. With this bandwidth, a 1000 x 1000 pixel image can be transferred at a frame rate of 30 frames per second, resulting in a PIV velocity sampling rate of 15 Hz. Since the fundamental frequency in the flow of interest is 1.2 Hz, the sampling rate is more than one order of magnitude higher than needed and is thus considered sufficient for most feedback control applications.

The unavailability of a commercial system could be overcome by new software development using commercially available toolboxes and off-the-shelf hardware, and thus posed no insurmountable obstacle.

Real-Time PIV Setup

Based on the properties of the available sensing systems surveyed in the previous section, a real-time PIV system (RT PIV) was determined to be the only viable choice to meet the demands of the experiment. At the time the Air Force Academy already owned a commercial off-the-shelf system manufactured by Dantec[2]. Therefore an attempt was made to keep as much of the original hardware as possible, while designing a custom hardware / software solution to allow for real-time access to the

PIV data. The following two sections describe both the hardware and software design of the RT PIV system.

Hardware

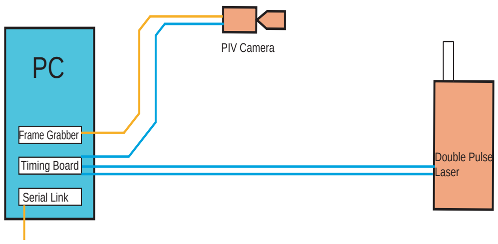

FIGURE 1. Hardware setup of real-time PIV system.

The off-the-shelf system available at the Air Force Academy consists of a Dantec PIV 2100 Processor unit, a Kodak Megaplus ES1.0 double frame CCD camera, and a New Wave Gemini 150mJ Double Pulse ND:YAG laser. In this configuration, a dedicated signal processor controls timing and accomplishes the image correlation so that the personal computer connected to the PIV processor only serves as a user interface to display data and initiate processing actions. There is very limited external triggering capability, making the system unsuitable for data capture at operator-specified times. The PIV processor is connected to the personal computer through a 10BaseT Ethernet connection. This connection poses a bottleneck in terms of data throughput, and thus must be eliminated for real time processing.

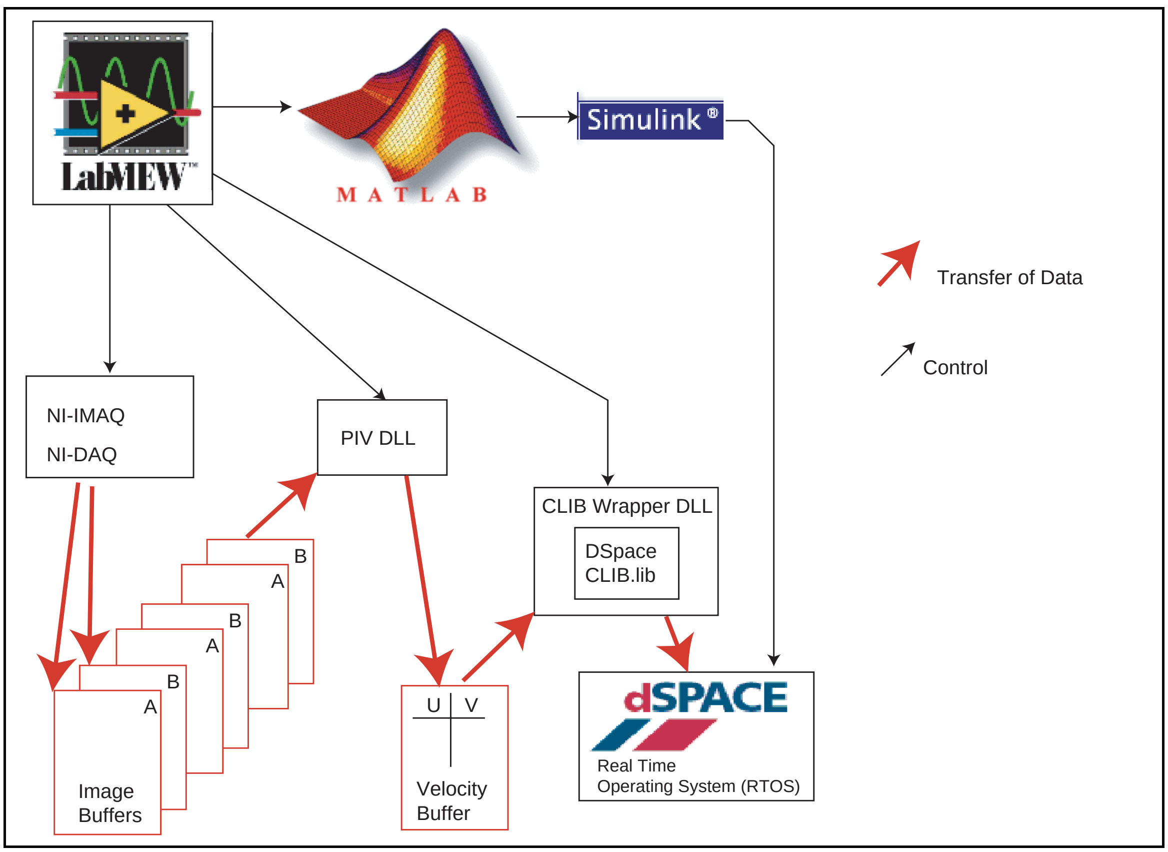

FIGURE 2. Software Setup of Real Time PIV system.

In-House System	Original System (COTS)
On-line operation, real time	Only off-line operation
Advanced trigger capabilities	Limited synchronization options
Interfaces to Matlab, LabVIEW, Tecplot, C	Only ASCII export
Modular, open architecture, easy to modify, hardware independent	"Black Box", closed, fixed system, no customization possible
>3k vectors/s in direct correlation	~2k vectors/s in frequency domain
Data available on-line in PC memory – 1000x faster	Data must be uploaded from processor (slow)
Source code owned by the user, available in public domain for non-commercial use	No access to source code, additional license is $14,000
$3,500 for hardware (excluding camera, laser and PC)	$40,000 for hardware (excluding camera, laser and PC)
Data acquisition rate 30 camera frames per second to PC memory	Data acquisition rate 1.25 camera frames per second to PC memory
Multi-sensor real-time capability	No real-time capability

Table 2.Comparison of the capabilities of commercially available and the newly developed systems.

For the RT PIV setup, the functionality of the processor was replaced by a National Instruments PCI-6602 timer board and a National Instruments PCI 1424 frame grabber card installed in a 1 GHz Pentium class personal computer (see Figure 1). The Laser and CCD Camera are the same as in the original Dantec setup. The overall hardware configuration is similar to what other PIV manufacturers (LaVision, Integrated Design Tools) are currently offering, in that the image correlation is accomplished by a PC rather than by a secondary processor. In that aspect the Real-Time PIV setup does not add anything new with respect to hardware, but rather uses off-the-shelf commercially available components. Using a frame grabber card capable of direct memory access (DMA) allows for direct acquisition of the camera images to the random access memory (RAM) of the personal computer, which is essential for real-time applications. DMA can be accomplished without placing any processing load on the CPU of the personal computer, which is therefore available to perform immediate correlation on the images from the camera as they arrive in RAM. It also eliminates the data bottleneck of the 10BaseT network interface.

Software

Since all commercially available systems are delivered with software that is compiled into an executable program, it was necessary to develop the software portion of the RT PIV system from scratch. To minimize the programming effort required, several commercially available toolboxes and programming systems were employed. Figure 2 shows the overall software layout. National Instruments' LabVIEW®, a graphical programming language, was used to handle image acquisition timing and user interface tasks. While it is most efficient in terms of programming and debugging speed and ease, its execution speed is not suited for real-time processing. Therefore computationally- intensive post processing and plotting tasks were done using Matlab®, which has more efficient memory management and advanced plotting capabilities. Also, Matlab®/Simulink® is a quasi-standard for control algorithm development and is being used to develop the feedback control algorithm that closes the feedback loop. This algorithm is then downloaded onto a dedicated signal processor manufactured by DSpace Inc. While Matlab® is more efficient in memory management and faster than LabVIEW in processing, it is not fast enough to accomplish the computationally intensive image correlations in real time. This is accomplished using software written in C and compiled in a dynamic link library (dll) which is called from within LabVIEW. The cross-correlation algorithm is a direct correlation as described in section 5.4.1 of Reference 1. This three-tier approach to programming minimized the implementation effort to about one man-month for the entire system.

Prior to data collection, image buffers are pre-allocated in PC memory, and the X-Y coordinates of the sensing locations of interest are defined. During a real-time run, a predetermined number of images are acquired into the memory of the personal computer as the frame grabber card transfers images from the CCD camera into the image buffers. As soon as a complete image pair has been acquired, the image correlation algorithm correlates both images at the chosen sensing locations only. Calculating a small number of sensing locations saves significant processing time over full field-of-view processing, and is the real enabler for real time operation. The resulting velocity information is then transferred to the real-time processor running the control algorithm, which then commands actuation, thus closing the feedback loop. At the end of the run, all image pairs remain available in memory and can be used to evaluate the effect of the feedback control onto the flow field as a whole.

Comparison of Capabilities

Table 2 compares the features of the system developed at the U.S. Air Force Academy with the original system supplied by Dantec. It shows that the new system is not only superior in performance as a real-time system, but also offers many advantages for open loop measurements due to its open software architecture. It supports existing data standards like the Hierarchical Data Format (HDF), an open standard for saving scientific data into binary files established by the national center for supercomputing applications (NCSA)[3]. As a superb research tool, it can be easily adapted to new requirements, whereas the canned, pre-compiled commercial systems typically require tedious workarounds.

Timing Analysis

To determine the actual performance of the real-time PIV system, a small simulink model was developed and compiled for the DSpace real time processor. The sole purpose of this model was to determine when an update of the velocity information was received through the high speed serial link. At that time one of the digital output lines would create a 1 ms duration TTL pulse. This pulse was routed to a spare timer on the timer board for time stamping. This setup therefore was capable of determining the time when the velocity information was updated, as well as the times when either of the laser pulses was fired. The time delay between the firing of the first laser and the time when the real time processor received the data is referred to as the total time delay.

Figure 3 shows how the total time delay varies depending on the difference in size between the primary and secondary PIV interrogation area sizes selected by the user. This difference determines the maximum pixel displacement in x and y direction that can be detected. Since the subpixel interpolation scheme used to evaluate the correlation result is limited in precision to about 0.1 pixels, the maximum detectable displacement also influences the measurement accuracy. While a larger maximum detectable displacement yields more accurate velocity results, it requires more computation time. As the maximum detectable displacement applies to two spatial directions, the number of calculations increases with the square of the maximum detectable displacement. This is reflected in the good agreement between a second order polynomial fit shown in Figure 3 along with the measured time delay data.

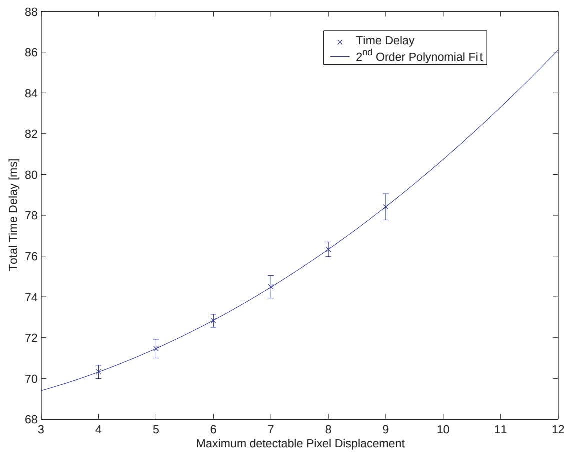

FIGURE 3. Time delay for different interrogation area sizes. Interrogation area taken from the first image is fixed at 32 x 32 pixels, interrogation area taken from the second image is larger by twice the detectable pixel displacement. 6 interrogation areas are being correlated. Time delays are averaged over 30 measurements, error bars show one standard deviation.

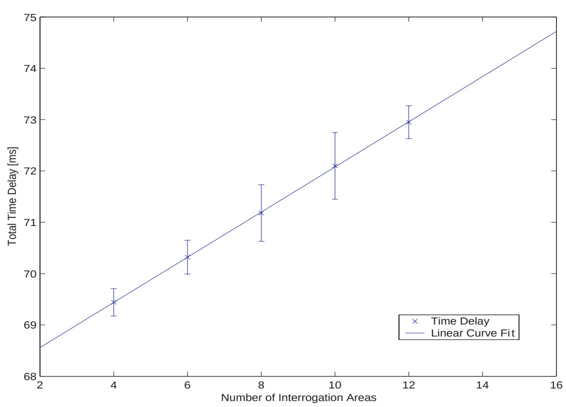

FIGURE 4. Time Delay for different numbers of interrogation areas. Interrogation area extracted from first image is 32 x 32 pixels in size, interrogation area from second image is 40 x 40 pixels. Total time delay averaged over 32 acquisitions, error bars depict one standard deviation.

The time delay is also linearly related to the number of sensor locations (interrogation areas) that are processed. This effect is shown in Figure 4. It can be seen that the time delay increases by 0.4 ms for each additional sensor location. This added time delay is small compared to the time delay incurred due to image transfer delays, for moderate numbers of interrogation areas.

Conclusions

A real-time capable particle image velocimeter has been developed for use in low speed water tunnel applications. Custom software was written to operate a commercially available off-the-shelf camera, laser and data acquisition. The performance of the system in terms of velocity measurement accuracy is equivalent to commercial systems. The time delay for processing the image information is in the order of 0.44 ms per velocity vector, plus the transfer times for both data and images. The overall time delay for a typical setup where 6 interrogation areas will be correlated in real time is on the order of 70 ms. Comparison to the fundamental frequencies encountered in the water tunnel experiments under consideration are on the order of 1 Hz which indicates a time delay of approximately 7 percent of one shedding cycle. For a moderately robust control algorithm this value is very acceptable.

References

1.M. Raffel, C. Willert, J. Kompenhans, "Particle Image Velocimetry", Springer, 1998.

2.Dantec Inc. "User Manual for PIV 2100 Processor and FlowMap Software", see http://www.dantecmt.com.

3.HDF User's Guide Version 4.1r3 1999, http://hdf.ncsa.uiuc.edu

4.Gillies, E. A., "Low-dimensional control of the circular cylinder wake", Journal of Fluid Mechanics, Vol. 371, pp. 157-178, 1998