Real-time Particle Image Velocimetry for Closed-Loop Flow Control Applications

Christian E. Willert[1], Matthew J. Munson[2], Morteza Gharib[3]

1: DLR Institute of Propulsion Technology, German Aerospace Center, 51170 Köln, Germany, chris.willert@dlr.de
2: California Institute of Technology, 1200 E. California Blvd, MC 205-45, Pasadena, CA 91125, USA, munson@caltech.edu
3: California Institute of Technology, 1200 E. California Blvd, MC 205-45, Pasadena, CA 91125, USA, mgharib@caltech.edu

Abstract Particle image velocimetry (PIV) has been a standard laboratory technique in experimental fluid mechanics for many years, allowing quantitative visualization of fluid flows. Typically, the particle images are captured and then are subsequently subjected to image processing to eventually yield vector fields. In this paper, we describe a system that allows for "real-time" processing of the image pairs followed by post-processing to immediately provide fluid mechanical quantities not accessible with conventional point wise measurement techniques. In effect the real-time flow field data acts as a sensor in a flow control experiment. This paper will discuss the design, implementation and performance of the system as it applies to control of vortex formation processes on a low Reynolds number airfoil inside an oil tunnel facility.

1. Introduction

Since its first introduction more that two decades ago particle image velocimetry (PIV) has evolved into an established laboratory technique in experimental fluid mechanics. The technique allows quantitative visualization of fluid flows, exposing the dynamics in a manner that can directly contribute to a physical understanding of the underlying flow physics. Once sufficient physical insight has been gained about a particular flow, one often considers manipulating the governing mechanisms to achieve a desired result. This is especially true when control of the flow under investigation might have a significant impact on the performance of engineering systems.

Typically, a flow control experiment attempts to achieve some change in system dynamics, often through amplification or suppression of flow instabilities. This is accomplished through the use of one or more actuators to produce a disturbance within the flow. If the flow is sufficiently receptive to the created disturbance, the dynamics of the system can be modified. Monitoring the effectiveness of the actuation through sensor measurements allows for the possibility of closed-loop control. Many flow control experiments utilize a small number of single-point sensors, which often only measure some characteristic of the flow. Flow dynamics often must be inferred from these point-wise signal measurements.

The use of PIV as a noninvasive, full-field sensor has the potential to yield much richer knowledge of the system dynamics and actuator effectiveness in the presence of control especially since it provides topological, full field information. The challenge of using PIV as a sensor in a closed-loop system is mainly due to the time delays involved in acquiring and processing the image data [1,2]. Long delays between the measurement and the actuation events will inadvertently lead to ineffective control strategies because the flow will likely have evolved such that the computed actuator input is no longer appropriate.

The present paper addresses these issues and presents an implementation of a "real-time" PIV (RTPIV) acquisition and processing system that is tailored to the time scales of an experiment, minimizing the effect of the time delays on control. The feasibility of the PIV based flow control concept is demonstrated in the low Reynolds number oil tunnel facility at the California Institute of

Technology using a flow experiment in which the time constants are in the range of the RTPIV response time.

2. Real time PIV system design

The basic system architecture is outlined in Fig.1 and consists of the flow experiment itself, the PIV acquisition and processing system and the active flow control subsystem. In the current implementation the PIV camera continuously streams image pairs of the flow into a PIV processing engine which is capable of processing the data at a sustained 15 Hz frame rate. The PIV processing involves a multi-grid adaptive scheme using a conventional FFT-based cross-correlation implementation and Gaussian fit sub-pixel peak position estimation [3]. The final validated vector maps are then used to compute flow statistics as well as differential quantities (e.g. vorticity maps) and integral quantities such as circulation or local (in-plane) mass fluxes.
Fig. 2 illustrates the inherent delays present in the described system. The principle bottle-neck is the image acquisition itself in which the camera can only provide the image after completion of the exposure period. In practice this time scale is on the order of the camera frame rate, here 30 Hz. Since two images are necessary for PIV the effective framing rate reduces to 15 Hz resulting in a corresponding time delay of 67 ms before the PIV processing can commence. The PIV analysis and post-processing can be performed within about 30 ms such that the system delay time in on the order of 100 ms for the current choice of hardware components. This image pair acquisition delay along with the response time of the actuator system comprises the inherent delay time in the control cycle.
The current PIV system offers only moderate performance since it relies on an off-the-shelf machine vision CCD camera with USB interface and cannot be operated in the double-shutter mode characteristic of state-of-the-art PIV cameras. Although slightly more expensive, a camera with interline transfer CCD sensor was favored to a CMOS sensor simply because the latter generally does not provide global shuttering that would allow frame straddling methods to be applied. Frame straddling is an asynchronous mode illuminating the scene with (laser) light pulses that allows the pulse delay to be shorter than the frame rate of the camera.

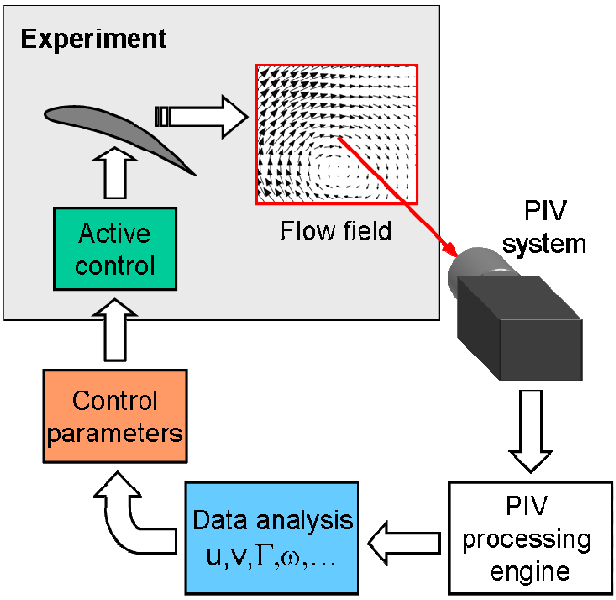

Fig.1: Schematic component layout incorporating a PIV system as a flow control sensor.

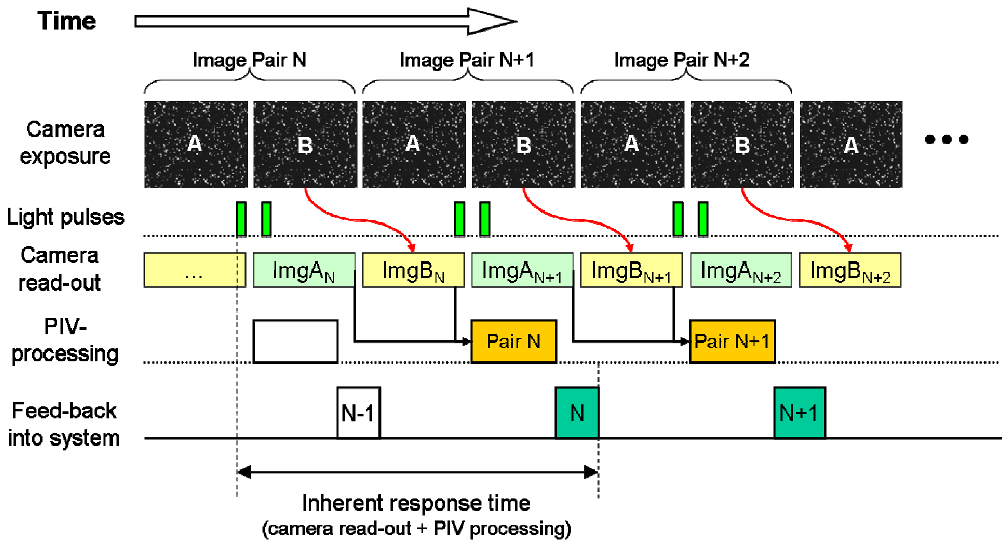

Fig. 2: Timing sequence of real-time PIV system

3. Experimental setup

3.1 Low Reynolds Number Oil Tunnel Facility

The Low Reynolds number oil tunnel facility at Caltech is a recirculating facility that uses mineral oil as the working fluid. The working fluid has a specific gravity of 0:835 and a viscosity of 13 cP. The facility has a square test section of 50 x 50 cm^2 and provides flow speeds of up to 25 cm/s. For a 10 cm characteristic body length, this corresponds to a maximum body Reynolds number of roughly 1500. The facility is temperature controlled via cooling loops in the return section of the tunnel to within 0.1°C in order to keep the viscosity constant.

The choice of mineral oil as a working fluid was made in order to provide slow enough time scales to facilitate closed-loop control efforts on micro-air vehicle sized objects. A typical Strouhal number corresponding to bluff body shedding is 0.2. Using the body size and flow speed above, this corresponds to a shedding frequency in the neighborhood of 0.5 Hz. The Reynolds number scaling ends up very close to that of air, (ν_{air} = 1.46(10e5) m2/s, ν_{oil} = 1.56(10e5) m2/s), but the forces are magnified the forces by almost 700 times, which makes them much easier to measure. A water facility would generate similar forces to those in oil, but the Reynolds number would be two orders of magnitude higher.

The experimental model is mounted from above and the free surface is mostly elimated by a slatted lid that allows for the passage of the sting. The model is attached to a six-axis force balance in order to measure the loads and moments.

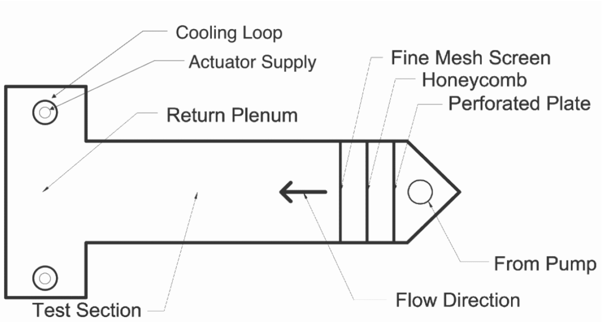

Fig. 3: Oil tunnel facility

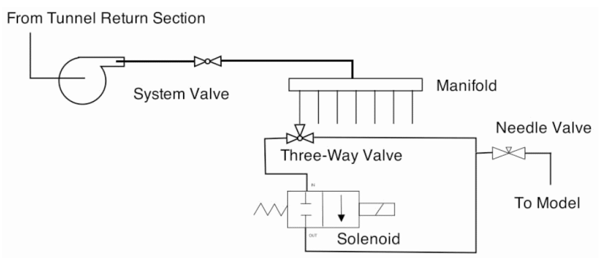

Fig.4: Flow control actuation system implemented in the oil tunnel facility showing one of 7 channels

3.2 Flow Control Setup

The model for these experiments is a NACA 0012 profile wing with 10 cm chord and aspect ratio two. A sting is necessary to hold the wing in the tunnel and also provides channeling to actuator slots that are embedded within the wing model. The sting is streamlined and engages the model near the trailing edge on the pressure surface, since the primary interest is on the dynamics of the suction surface. Seven slots, each 1 mm wide and 25 mm long, are arranged along the span of the wing at the midchord and are directed downstream.
The actuation fluid is supplied by an auxiliary pump connected to the return section of the tunnel. Each channel is quasi-independent from the others, but they share a common manifold. Figure 3 shows the architecture of the actuation system. Each channel can be supplied with a steady or unsteady flow rate. Unsteadiness is generated by a solenoid in the supply line, capable of oscillating at frequencies up to 10 Hz. The flow rate through each channel is regulated through a needle valve before finally being sent to the actuator slot.

3.3 PIV System

The illumination for the DPIV system is provided by a Nd:YAG laser with a 532 nm wavelength (Gemini PIV, New Wave). A light sheet is created by passing the beam through a cylindrical lens and then turned up through bottom of the test section by a mirror. The mirror is on a linear traverse, which allows the spanwise placement of the light sheet in the tunnel.
The flow field is observed by the CCD camera (UI-2230SE-M, IDS GmbH) perpendicular to the light sheet, which passes through chordwise through the experimental model. The frame synchronization output from the camera (30 Hz) is first divided by two (15 Hz) and then fed into the timing unit used to control the laser. In this configuration the camera serves as master clock in the recording system.
Flow control is achieved using through a low-cost, multi-channel digital output system (USB-1208LS, Measurement Computing), whose output drive the solenoids of the actuation system. PIV processing is currently implemented on a standard dual-core PC system and does not make use of parallel processing offered by the multi-core architecture.

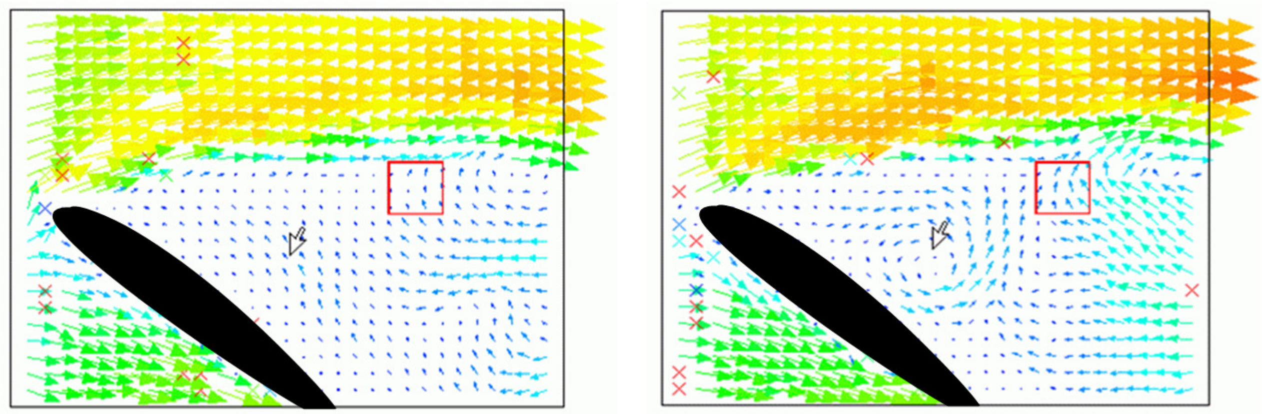

Fig. 5: Screen captures from a continuous PIV data stream of the RTPIV software showing separated flow around a NACA0012 airfoil at Re = 1050, without tangential blowing (left) and with blowing from all seven actuator slots (right). Color coding represents vector magnitude, outlier vectors are marked by red crosses. The red square defines a sampling contour for flow quantity calculation.

4. Results

As the current version of the software discards images and recovered data after evaluation only screen shots of exemplary flow states can be provided at this point. Fig. 5 shows two vector maps of the flow at the symmetry plane of the NACA0012 airfoil at two different flow conditions, that is, with and without tangential blowing from the actuator slots. In this configuration the actuator flow

induces a counter-rotating vortex structure in the separated region above the airfoil. Circulation and field averaged vorticity are measured in real-time and used as control variables in the system.
Certain combinations of processing parameters may have a detrimental impact on the performance of the processing engine, causing the system to run at speeds much lower than the camera frame rate. This has negative implications for control, not only because the whole system is now running more slowly, but also because the control system will have potentially unpredictable updates. This is because the image pairs continue to stream into memory at 15 Hz, but if the processing engine isn't available to handle the images, they are discarded. This intermittency will lead to potentially long control command delays, which can have serious implications on the ability of the control to be effective.
A full examination of the performance of the software was not completed at the time of writing and will be available is a later version of this paper.

5. Conclusion

A system has been developed that allows for DPIV measurements to be used as a feedback sensor for flow control experiments. The performance of the method is sufficiently fast to capture flow events at 15 Hz with delays on the order of 100 ms. While this is a rather benign implementation of PIV-based flow control it nonetheless illustrates the concept of using spatially and temporal resolved data for the calculation of control parameters in a closed loop flow control system.
The moderate performance of the current PIV system, relying on an off-the-shelf machine vision CCD camera, will certainly be outperformed by camera systems with faster acquisition rates along with faster camera-to-host interface. Currently camera systems capable of providing 100 image pairs per second are commercially available which would reduce the image pair acquisition time to about 10 ms. It should be noted that current high-speed CMOS camera technology is not suitable for this type of application because the image data is unavailable to the host up until the completion of a recording sequence of a multitude of frames. The current trend toward multi-core processors and GPU-based processing will certainly reduce the inherent system delay even further enabling flow control on more complex experiments.

Acknowledgments

This work was funded in part under a Multi-University Research Initiative from the U.S. Air Force Office of Scientific Research. Student funding by the National Defense Science and Engineering Grant and the Science, Math, and Research for Transformation fellowship is gratefully acknowledged.

References

[1] Siegel S, Cohen K, McLaughlin T E, Myatt J (2003): Real-time particle image velocimetry for closed-loop flow control studies, Proc.: *41st Aerospace Sciences Meeting and Exhibit*, 6-9 January 2003, Reno, Nevada, Paper No. AIAA 2003-920

[2] Yu H, Leeser M, Tadmor G (2006): Real-time particle image velocimetry for feedback loops using FPGA implementation, Journal of Aerospace Computing, Information, and Communication Vol. 3, pp. 52-62

[3] Raffel M, Willert C, Wereley S, Kompenhans J (2008): Particle Image Velocimetry – A Practical Guide, Springer Verlag, Berlin Heidelberg New York