Three Component Planar Doppler Velocimetry Using Imaging Fibre Bundles

by

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ABSTRACT

This paper describes a planar Doppler velocimetry (PDV) technique that is capable of measuring the three, instantaneous and time average components of velocity over two dimensions using a single pair of signal and reference cameras. PDV can be used to measure the instantaneous 3D velocity of a fluid by using an absorption line filter to determine the Doppler shifted frequency of a narrow line-width, pulsed laser that has been scattered from particles seeded into the flow. In the technique presented here the three views required to obtain three component velocity information are guided from the collection optics to a single imaging plane using flexible fiber imaging bundles. These are made up of a coherent array of single fibers and are combined at one end as the input plane to the measurement head. A fourth leg of the imaging fiber bundle is used to image the individual laser pulses and allow correction for pulse-to-pulse frequency variations. As part of the development phase of the technique measurements are presented of the velocity field of a rotating disk using both an Argon Ion laser giving time average results and a frequency doubled Nd:YAG laser to give an instantaneous result. A typical vector map of the computed velocity is shown in Figure 1. In this figure vectors are shown at only 1 in 10 data points.

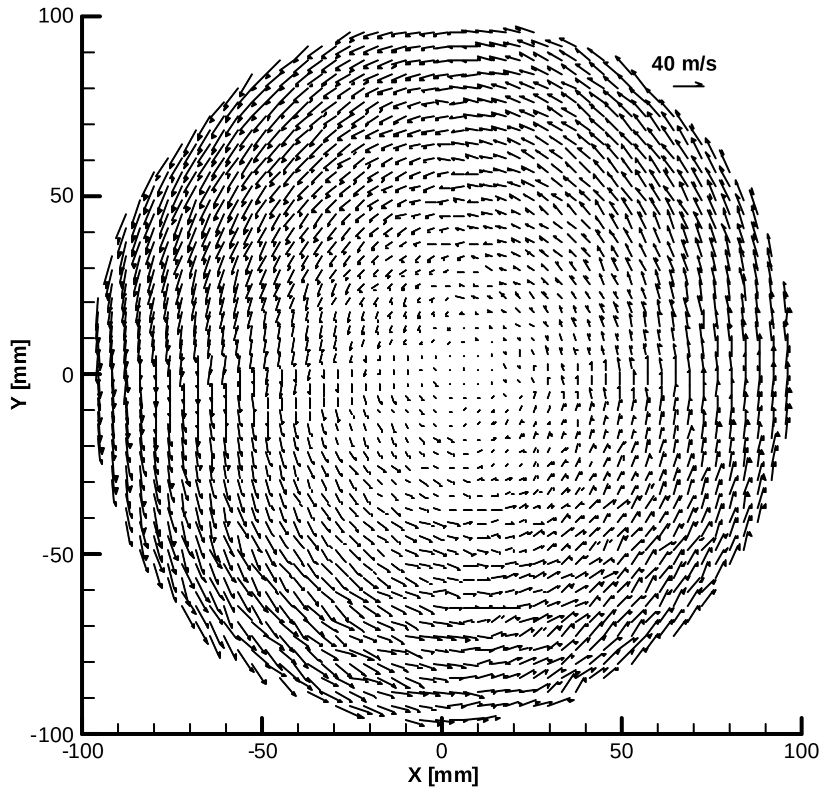


Figure 1. The time average velocity field of a rotating disk captured using and Argon Ion laser.

1. INTRODUCTION

Detailed information of flow properties and flow phenomena is an essential part of engineering design of flow systems and the development of the theory of fluid mechanics. With this in mind and with the advent of suitable hardware, new techniques to measure and investigate flows have been developed. One of these is Planar Doppler Velocimetry (PDV) (Samimy and Wernet 2000) with is also known in the literature as Doppler Global Velocimetry (DGV) (Meyers and Komine 1991).

General reviews of the development of PDV have highlighted two themes in the development of the technique (Samimy and Wernet 2000, Mosedale, Elliott, Carter and Beutner 2000, Elliot and Beutner 1999, Reinath 1997). The first is the development of systems for three component velocity measurements over a plane using two-dimensional array cameras. The high cost of these devices has pushed researchers to minimize the number used in the technique. The second focuses on ongoing problems in the development of PDV on system stability and especially the behavior of the light source used. The latest implementation of ideas into PDV and some of the latest applications are reported in a special issue of the journal *Measurement Science and Technology* (Tropea 2001). Building on this work, this paper describes the development of a novel PDV system that addresses these two themes.

2. BACKGROUND

The theory of PDV is based on the Doppler principle that light, when scattered from a moving object is frequency shifted depending on the velocity of that object. The Doppler formula describes the relationship between the velocity of the object and the frequency shift of the light scattered from that object and can be expressed using the vector equation

$$\Delta u = \frac{u_0}{c}(\boldsymbol{o}-\boldsymbol{i})\bullet \boldsymbol{V} \qquad (1)$$

Here, $\Delta\upsilon = \upsilon_D - \upsilon_o$ is the difference between the Doppler shifted frequency (υ_D) and the frequency of the light source (υ_o), c is the free space speed of light, $\boldsymbol{V}$ is the velocity vector of the object that is scattering the light and $\boldsymbol{o}$ is a unit direction vector to the viewer and $\boldsymbol{i}$, the unit direction vector of the light source. A physical interpretation of this equation can be developed for the two-dimensional case when the light source and the viewing direction are in the same plane, as shown in Figure 2.

From Equation 1 it can be seen that to determine the velocity of the scattering object, the Doppler shift of the scattered laser light needs to be determined as well as having knowledge of the propagation direction of the light source and the direction from which the scattered signal is collected. While the light source and viewing direction can be easily determined, a method for determining the Doppler shift of the light frequency is needed. The PDV technique measures the shift in frequency directly using a frequency-to-intensity converter. Essentially, a filter that attenuates the scattered signal based on the frequency of that signal. For this filter to be efficient, it must have a cut-off that extends over the maximum expected range of velocities. For this a basic example of the expected performance of the filter can be developed. If a laser at a wavelength of 532nm is used as the light source and the minimum to maximum expected velocity range is +/- 100m/s then the Doppler shift will be +/- 200MHz depending on $\boldsymbol{o}$ and $\boldsymbol{i}$. In this example the filter will then need to have a maximum cut-off for just over 400MHz.

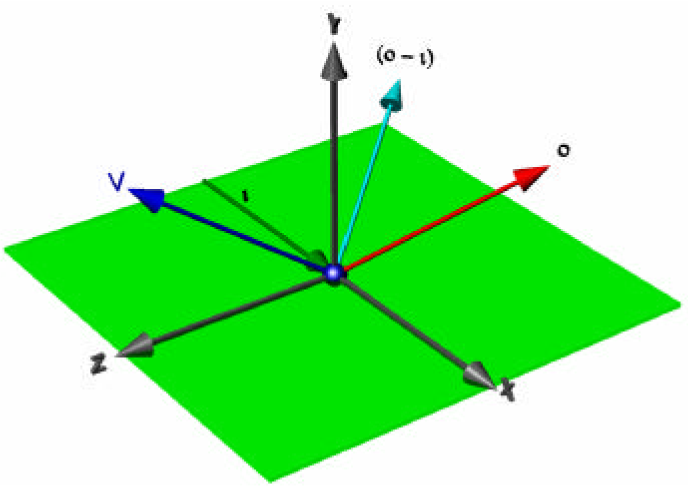
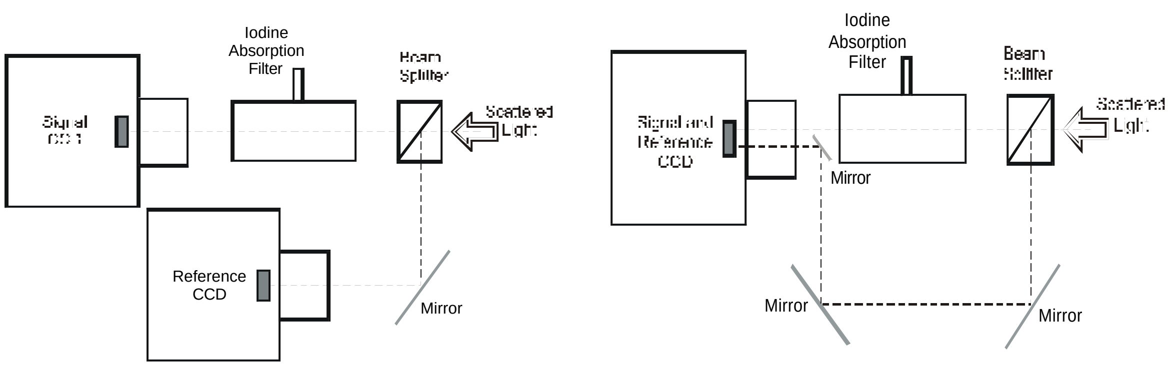


Figure 2. A schematic of the Doppler principle: ***V*** *- vector of the scattering particle,* ***i*** *- light illumination vector,* ***o*** *- observation vector,* ***(o - i)*** *sensitivity vector.*

For such a narrow operation range Komine (1990) identified the use of the atomic and molecular absorption bands. These absorption bands are spectroscopic lines and are at specific frequencies that equate to the energy transfer levels of the substance used in the filter. Several substances have been identified that have suitable properties that could potentially be utilized (Miles, Yalin, Tang, Zaidi and Forkey 2001; Chan, Heyes, Robinson and Turner 1995). Of these substances, iodine has an absorption band in the narrow tuning range of commercial Argon-ion laser and several absorption bands in the larger tuning range of Nd:YAG lasers (Miles *et. al.* 2001).

The philosophy of the PDV technique is to tune a narrow line-width laser light source to a point that is half way either up or down the side of an absorption band (Elliot and Beutner 1999). For no shift in the laser frequency, or zero velocity measured, the detector will see a signal of 50% the value of full transmission. Any Doppler shift in the laser frequency will be measured as a change in the signal intensity level. The sign of the velocity direction of the measured component can also be determined from the direction of the shift to either lower or higher intensities.

Early in the development of PDV it was realized that to obtain usable data a reference signal was needed (Komine 1990). The reference signal split off before the filter is used to normalize the signal measured through the filter, correcting for variations in the scattered intensity. There are two sources that vary the intensity of the scattered signal. The power of the light source can vary in time as well as the scattering efficiency of the scattering medium. For measurement of flow velocities, a laser can be spread into a light sheet. The power distribution in this sheet can vary spatially across the sheet and in time. The flow is seeded with particles that are designed to follow the flow (Meyers 1991). The amount of seeding and the size of the particles affect the scattering efficiency and hence the intensity of scattered signal. Hence, by normalizing the signal with a reference the effect of intensity variation due to laser power fluctuations and seeding density can be removed.



(a) (b)

Figure 3. (a) The arrangement of equipment used in a standard PDV head and (b) the arrangement used in a split view PDV system.

Other than the work of Roehle and coworkers (Roehle 1996; Roehle, Schodl, Voigt and Willert 2000) all other systems found by the authors in the literature follow the general scheme of a single laser source and multiple viewing directions. Initial work used CW lasers (Komine 1990; Ford and Tatam 1997). However, many research groups quickly moved to pulsed, frequency doubled Nd:YAG systems (Elliot and Beutner 1999, Nobes, Ford and Tatam 2002) with the main aim of increasing the available laser power while at the same time making instantaneous velocity measurements possible. Meyers and Komine (1991) began the initial work in the area using a CW Argon-ion laser and their technique is perhaps the classic arrangement of PDV. Here, six cameras in three pairs of signal and reference cameras viewed a region of interest from three different directions, each pair utilizing its own iodine cell. This style of arrangement of the two cameras is shown in Figure 3(a). Some of the reported difficulties with this system included the need to develop frame grabbers that could sample from two cameras at once (not commercially available at the time), integration of a network of computers to control and drive the equipment, low signal to noise from the interlaced frame cameras used, differential sensitivity of the different iodine cells and the laser to vibration and temperature and the extensive development of software for control of the experiment as well as the processing of data. Other researchers have addressed some of these problems by changing the layout and philosophy of the equipment. To increase laser power and provide instantaneous measurements frequency doubled Nd:YAG lasers have been incorporated (Reinath 1997). The introduction of digital technology has seen the use of CCD cameras and commercial frame grabbers that support multiple cameras. Cooled CCD cameras can also provide high signal to noise as well as higher data depths up to 16 bit (Meyers, Fleming, Althoff Gorton and Berry 1998). These are expensive however, which has triggered the development of a number of novel arrangements to reduce the number of cameras used. One alternative has focussed on using a single camera to detect both the signal and reference images (Smith, Northam and Drummond 1996). A typical arrangement of the split view technique is shown Figure 3(b). Viewing from three directions, this reduces the number of cameras from six to three at the expense of lower spatial resolution.

For any of the layouts of the detector equipment, frequency drift of the laser is an important problem, especially for pulsed Nd:YAG systems. For these lasers an injection seeded laser is used to tune the host laser. The seed laser has a narrow line width (~5kHz) CW laser at the fundamental frequency of the host laser (1064nm). This seed laser, which is frequency tunable by changing the temperature of the cavity crystal, is introduced into the cavity of the host laser and because its power is orders of magnitude larger than the noise in the system, the host laser builds up preferentially around this frequency. To help lock the host laser to the seed laser the length of the cavity of the host laser is adjusted. This is done in a feedback manner with the position of one of the mirrors of the host being dithered. The resultant is an output that can be tuned over the gain curve of the host laser by tuning the seed laser and dithers about the frequency of the seed laser. The amount of dither is dependent on the setup of the whole laser system but can be of the order of 100MHz. To counter this movement of the frequency of the host laser many research groups have employed a system to measure the frequency of the laser for the pulse that is used to take the measurement. A typical system is an arrangement of single point detectors and a separate iodine cell (Mosedale *et. al.* 2000; Elliot and Beutner 1999).

3. EXPERIMENTAL SETUP

The PDV system under development at Cranfield University has been designed to address several of the problems and limitations of PDV systems that have been reported in the literature. Overall, the following criteria have focused the structure of the current PDV system. The PDV system will aim to;

- Measure the three components of velocity over a plane
- Be capable of both instantaneous as well as time-average measurements
- Measure internal as well as external flows
- Minimize the number of cameras used
- Address problems of laser stability
- Address problems of stability of the iodine cell

To achieve these aims a system has been developed that uses the philosophy of one illumination direction and three viewing detectors. A schematic of the experimental arrangement is shown in Figure 4. To achieve the aim of instantaneous measurement of velocity a pulsed Nd:YAG laser is used (Spectra Physics GCR 190-30). This laser is capable of producing 300mJ @ 532nm. A second CW laser (Lightwave Model 101) is coupled to and seeds the host laser at the host laser fundamental frequency of 1064nm. I/O communication through the diagnostic port of the seed laser allows control of the seed laser frequency over a range of 20GHz as well as providing information on the seed laser temperature, the voltage being provided to the piezo-mirror and the build-up-time (BUT) error voltage. This information is used to assess the state and performance of the laser. The output from the host laser is frequency doubled to 532 nm using a second harmonic generator and this is used as the light source for the experiment. The laser pulse is spread into a light sheet using a combination of spherical and cylindrical lenses.

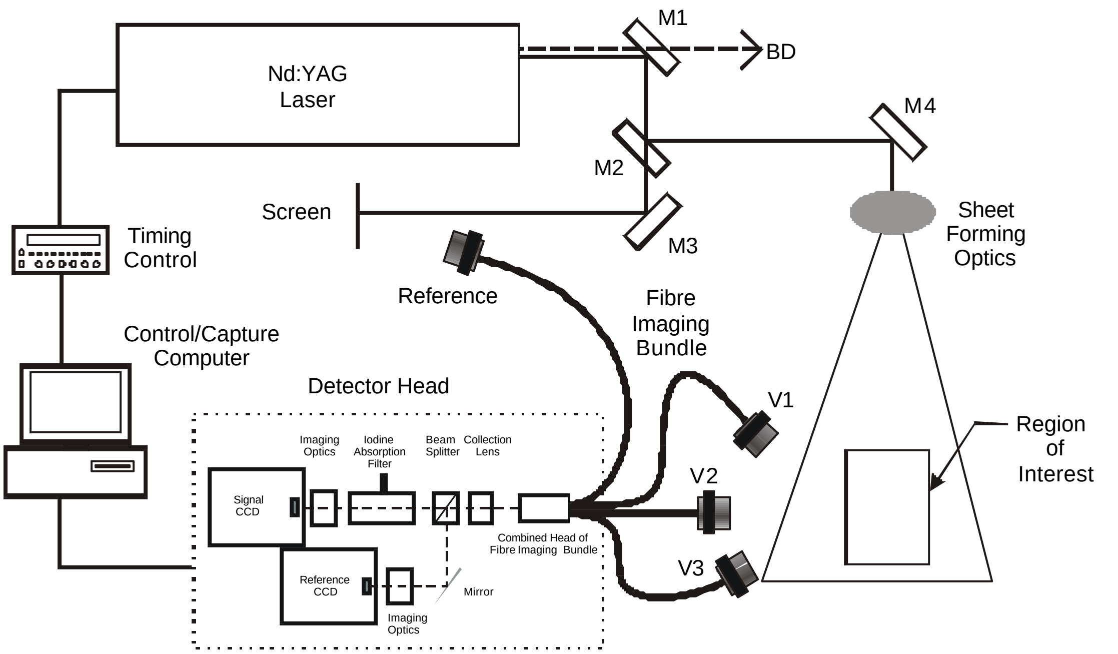


Figure 4. A schematic of the experimental arrangement for the PDV experiment. — 532nm beam; -- 1064nm beam; M1 and M2 – 532nm dicroic mirrors; M3 and M4 – turning mirrors, BD – 1064nm beam dump

A unique feature of this PDV system is that a single head is utilized consisting of two cooled CCD cameras (LaVision Imager3) and a single iodine cell. The cameras operate at –15°C giving low noise performance. The arrays are 1280x1024 made up of square 6.7µm pixels and images collected are digitized to 12 bit. A single iodine cell is enclosed in a heated oven and iodine concentration in the cell is controlled by temperature control of a cold finger. Two PID controllers control the temperature of the oven and the cold finger to within 1°C. A schematic of the detector head is shown as a sub-figure in Figure 4. Note this has the same basic layout of cameras and iodine cell as the single component head shown in Figure 3(a). The imaging optics port an image into the head system that is first split into two paths with a 50/50 non-polarizing beam splitter. One path is directed to the reference camera via a turning mirror, this corrects the orientation of the image, while the second is directed through the iodine cell to the signal camera.

The image coupled into the detector head is delivered to it by an imaging fiber bundle. This is a coherent array of fibers that is split into four channels. Three of these are used to view the same region of interest from three different directions. The fourth, as shown in Figure 4, images a small percentage of the laser pulse that has passed through a 532nm dichroic mirror and scattered off a screen. This provides a means of monitoring the frequency of each laser pulse. To demonstrate the combining of channels an example image from the signal camera of the combined three views and the laser beam reference view is shown in Figure 5. The top left (View A) and bottom right (View B) and left (View C) are the three views of a reference target of crosses and views an area 200x200mm. The perspective distortion of the target highlights the different directions of the three views. The top right corner of the image in Figure 5 is the fourth channel used to image the laser beam.

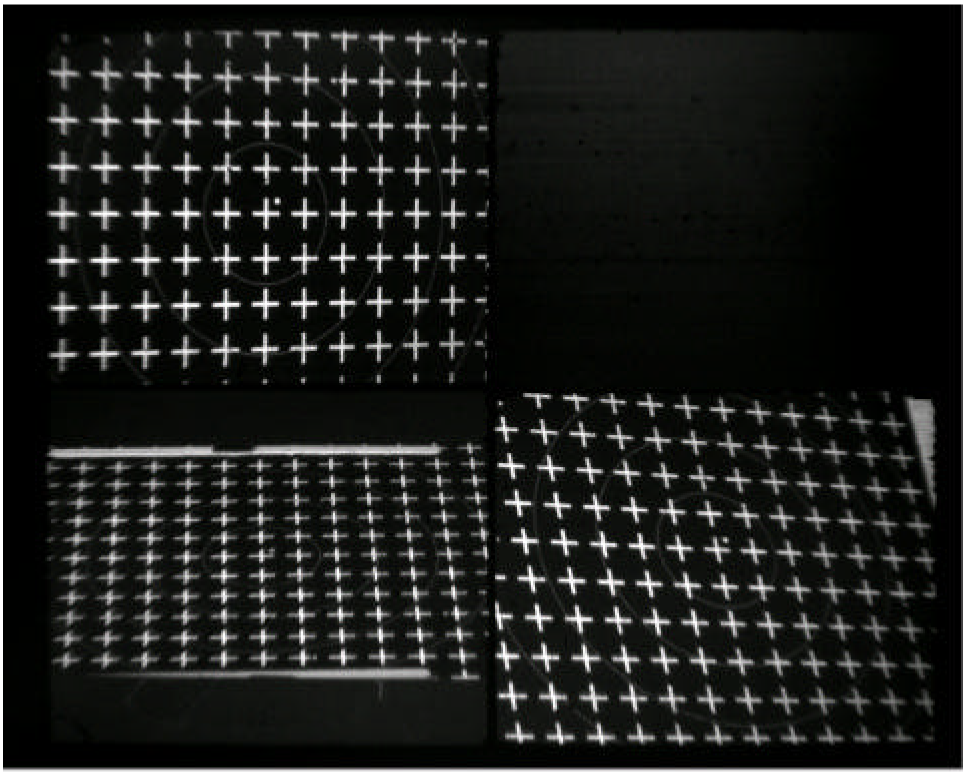


Figure 5. An example image of the view through the image bundle of a reference target captured with only one camera. The area viewed of the target is 200x200mm.

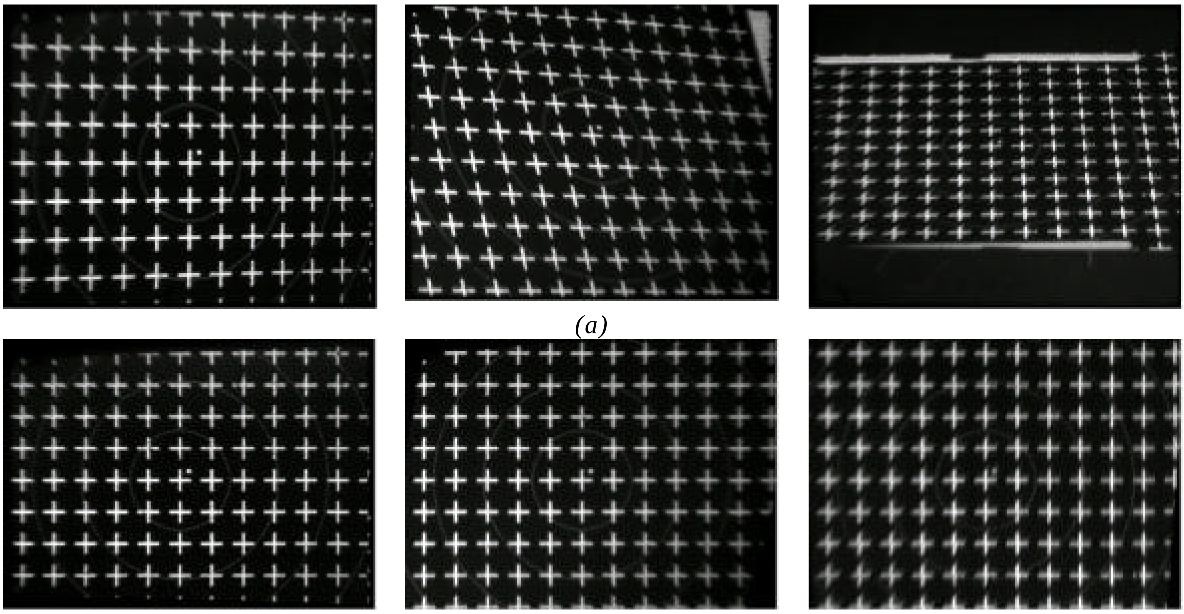
The use of the imaging fiber bundle reduces the total number of cameras used to two. The inclusion of the referencing channel allows the system to use only a single iodine cell. Imaging the pulse for frequency referencing also allows the distribution of laser power in the pulse to be recorded as well as the frequency distribution across the beam wave-front.

4. PROCESSING PROCEDURE

Camera control, image capture and processing for the PDV system have been integrated into a single software bundle that is based on the cameras control macro language (LaVision *DaVis 6.0*). The macro language allows for the capture, processing and display of data as well as a facility to port data to C/C++ DLL functions for specific and fast processing. Several functions included in the software are incorporated into the processing of the PDV data.

The use of the imaging fiber bundle to capture all three views onto a single image has introduced extra processing of the collected images compared to a system that has three completely separate heads for each view. As part of the collection process, the two raw images from the signal and reference cameras have had a background subtracted. This background is the noise accumulated in the exposure as well as the read out noise. Before proceeding with processing the data to velocity vectors, each separate view is extracted from the raw images into separate buffers. These buffers are then de-warped and the data interpolated and mapped onto a regular grid. The de-warping coefficients are first defined using a target image of crosses. A captured image of the target is presented in Figure 5. A central cross, nominated as the origin of the region of interest is marked with an identifying dot. In the de-warping procedure for determining the de-warping coefficients the physical spacing of the crosses is entered into the software and the cross identifying the origin is interactively selected as well as the cross to the origin's immediate right. The software then searches through the image locating the center of the crosses using a correlation method. In determining the de-warping coefficients, the location of the crosses is first mapped to a normalized space of –1 to 1 across the image and bottom to top of the image. The de-warping coefficients are then determined from curve fitting a third order polynomial. The data is then mapped onto a defined grid space with a calculated scale. The coefficients are stored for this specific view. Of the six views extracted from the signal and reference images, three from the signal and three from the reference image, a master view is selected and initially de-warped. All other views are first mapped to the normalized space and then mapped onto this master so that each view has the same origin within the image and each pixel has the same scale.

The top row of images in Figure 6(a) have been extracted from the target image shown in Figure 5 which is used to locate the origin of the velocity and provide scaling of the data field. The de-warping procedure has been used on these individual images and the resultant de-warped images of the three views are shown in Figure 6(b). In the images the reference mark used to define the origin can be clearly seen as well as reference circles about this origin. The circles have been used to maximize the overlap of each of the views. The extracted images are all of different size, however de-warped images have all been mapped onto a grid the same size. The amount of de-warping and interpolation of the images varies between images due to clear differences in the view perspectives. The procedure does however clearly map all three views onto the same space.



(a)

(b)

Figure 6. Views A, B and C of the target show in Figure 5: (a) extracted and (b) de-warped.

De-warping of the views corrects the images for distortion. There are several distortions that are present. There is a general perspective distortion in each view, which is a function of the viewing direction. The imaging system can introduce barreling or pincushion distortion. While these distortions are relevant for both cameras, there is a third distortion that is also present between the cameras. This is due to misalignment of the cameras and for any change in the magnification of the image after the beam splitter onto the image array of the cameras.

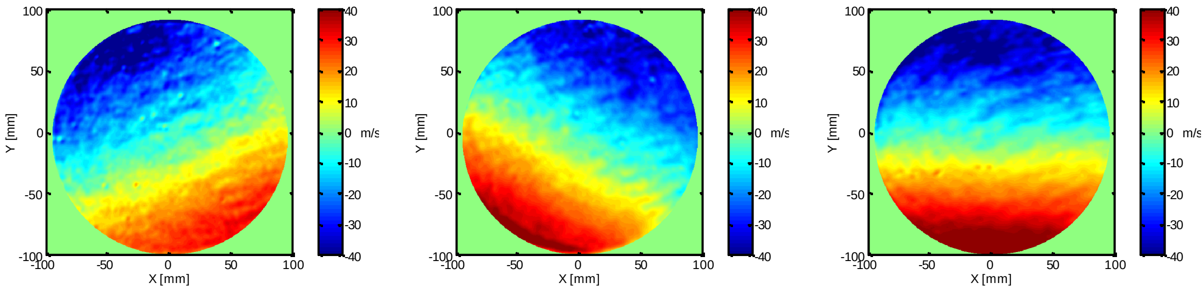
Once the data has been de-warped, interpolated and mapped it can be passed into a processing procedure to determine velocities. Before division of the signal and reference images, the data is corrected using a 'white card' correction and put through a low pass filter. The white card correction corrects the data for variations of signal sensitivity in the CCD and vignetting of the signal across the array. A low pass filter can be used to reduce the effects of laser speckle. After the division of each of the three views the intensity ratio is converted to frequency. This conversion is via a polynomial fit of the iodine transfer function. The transfer function of the absorption band used is measured by frequency tuning the laser across the range of the absorption band. This data is then fitted to a model of the absorption spectra using the code developed by Forkey (1996). After the conversion, the data at each point in the view is an absolute measurement of the scattered laser frequency. A measurement of laser frequency for the measurement pulse is determined using the same fitting procedure using the image of the laser pulse captured by the fourth leg of the fiber imaging bundle. The Doppler difference is then calculated and using Eq. 1 the velocity magnitude of the component defined by the laser and viewing direction can be calculated. This procedure is repeated for each of the three views. The data can then be mapped onto a regular orthogonal grid generating the three orthogonal components of the measured velocity over a plane in the reference frame of the experiment.

5. RESULTS

<u>5.1 The velocity field of a rotating disk</u>

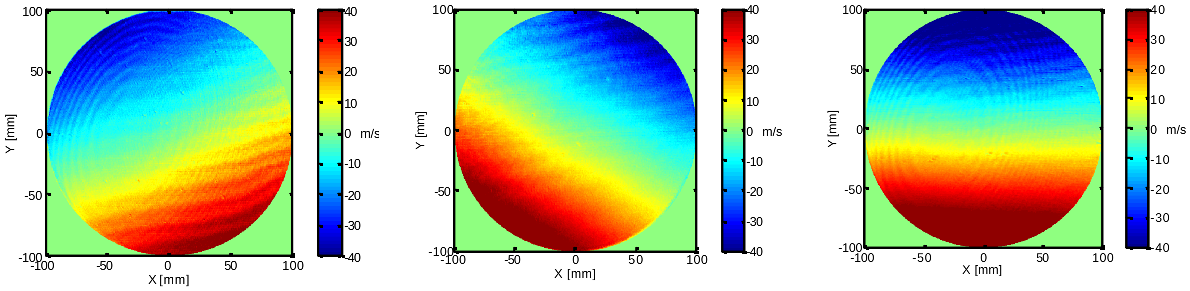
The system has been developed with a specific aim to measure velocities of a flow using particles seeded into the flow as the scattering medium. Any moving object however will Doppler shift a light source directed at it.

In the development stage of the system a rotating disk has been used to provide a moving field of a well-defined velocity. The data presented here are the processed results collected from of a rotating disk. The rotating disk is 200mm diameter that has been coated with flat white paint with the aim to give near uniform reflection. The disk is illuminated by the laser at an angle that is near perpendicular to the rotational axis. The three views are arranged so that all three are sensitive to the rotating field. Two laser sources have been used for the results presented here. An instantaneous results of the velocity field was collected using the pulsed Nd:YAG described earlier and a time average results was collected using the 514.5 nm line of a frequency stabilized Argon Ion laser (Spectra Physics 2010). The collection time of this measurement was 10µs compared to the 10ns of the near instantaneous result using the pulsed Nd:YAG laser.



View 1 *View 2* *View 3*

Figure 7. The computed instantaneous velocity field for the different views using a pulsed Nd:YAG laser



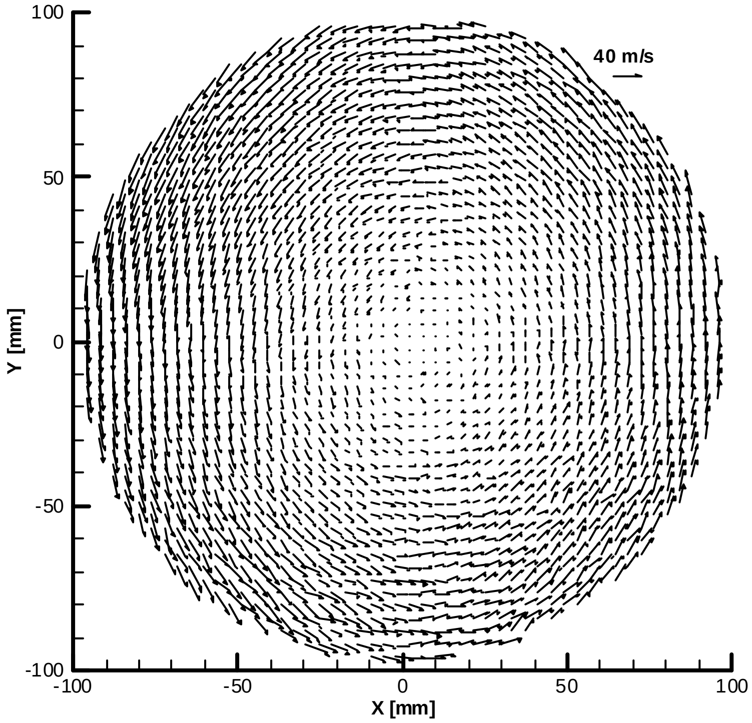
View 1 *View 2* *View 3*

Figure 8. The computed time average velocity field for the different views using an Argon Ion laser.

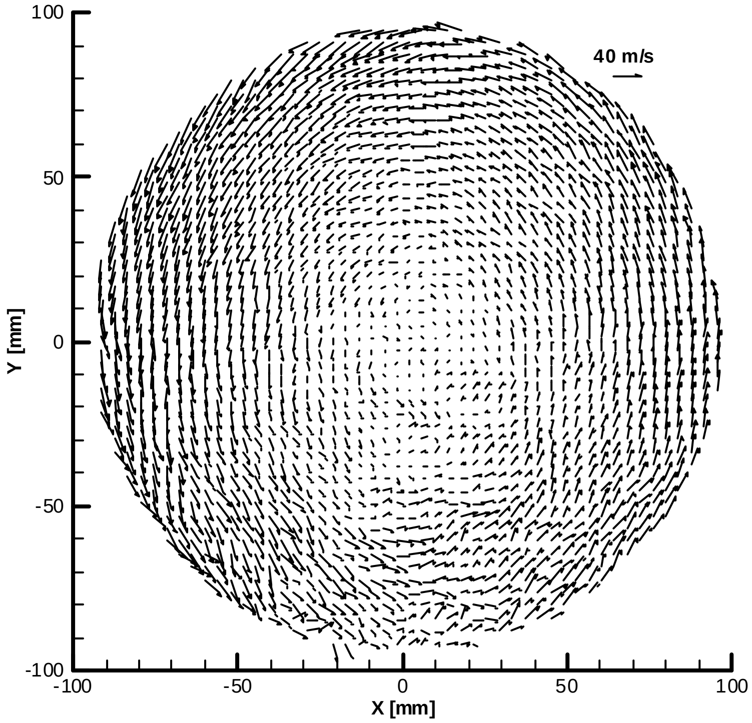
The computed velocity field for the three different views of the disk are shown in Figure 7, the instantaneous measurement using the Nd:YAG laser and Figure 8, the time averaged results using the Argon Ion laser. The instantaneous result in Figure 7 has been smoothed with several passes of a low pass filter to reduce the effect of speckle noise. The residual effects of laser speckle are however still evident in the image as well as the noticeable fluctuations over larger areas. This can be linked to pulse to pulse change in the distributions of the laser power across the wave front. A significant proportion of this effect is removed using the white card correction for laser power distribution however there is a small amount of AC fluctuation still present.

The time average of the velocity field produced using the Argon Ion laser shown in Figure 8 generates a significantly smoother velocity map. Note that no extra filtering or smoothing has been used. There are fluctuations present in the scalar field that are a result of a moving interference pattern generated by the sheet forming optics and moved by vibration of the laser (water cooling pump). The smoothing out of laser speckle through time averaging and better beam profile results in a smoother vector field as shown in Figure 9(b).

The vector maps of the velocity field shown in Figure 9 have been generated by mapping the scalar field of the three views in each data set onto a regular orthogonal grid. The transformation matrix is generated using the velocity maps and information of the view directions. In the vector maps, only ever 10^{th} vector has been shown. Noise present in the instantaneous data, Figure 9(a), result in a vector field that has some bad vector directions. However, generally the velocity field is representative of the velocity field that can be expected of the rotating disk. The smooth, less noisy results of the time average data, Figure 9(b) generates a significantly smoother velocity map that has correct direction and magnitude.



(a)



(b)

Figure 9. The processes velocity vector fields of the rotating disk. (a) Instantaneous using the Nd:YAG laser and (b) time average using the Argon Ion laser.

5.2 Errors

There are several areas within which errors to the calculation of a velocity vector using the PDV technique can be associated. The experiments investigating the velocity field of the rotating disk have highlighted the following sources of errors as potentially the most significant in the current technique.

(1) Image registration - This is the registration of the signal and reference image using the division. Accurate registration of the two images in principle would remove the noise introduced by laser speckle. However, varying polarization across the image would result in the presence of laser speckle after the division of signal and reference image.
(2) Modeling of the Iodine transfer function - The shape of the transfer function is critically dependent on the vapor pressure of Iodine in the cell and hence the operating temperature of both the oven and cold finger used to set the vapor pressure. As highlighted by other authors, the use of a starved cell will minimize these effects. Accurate modeling of the shape of the transfer function is however needed and assumptions of linearity or Gaussian shape of the function over the region of the measurement can led to significant errors.
(3) Measurement of laser frequency - The pulsed laser has a significant pulse to pulse frequency fluctuation that requires individual measurement of each measurement pulse frequency to correct each data point. The CW beam from the Argon Ion laser however has a long term drift that is significantly slow and lower in amplitude than the pulsed Nd:YAG which also must be measured if accurate velocities are to be determined.
(4) Image registration between views - Each view shown in Figure 7 & 8 have been mapped onto a single scale for that data set. The accuracy of how well these individual views register with each other well effect the result of the matrix mapping to the orthogonal representation of the data.

6. CONCLUSIONS

A PDV technique has been described that is capable of measuring the three instantaneous components of velocity over a two dimensional region. All three views needed to define a three-dimensional velocity field have been recorded using a single pair of signal and reference cameras by porting the three views through a fiber-imaging bundle. The legs of this bundle combine into a single array that is imaged through the PDV detection head. Laser frequency stability is monitored and measured using the fourth leg of the bundle allowing for correction for any frequency movement of the laser for each instantaneous measurement. The use of a single PDV detector head minimizes the number of CCD array cameras that are used to a total of two and only a single iodine cell is used for both measurement of the three velocity components and reference measurement of the laser frequency. Only a single frequency scan is needed to define the transfer function of the iodine cell for converting measured intensities to frequency. Any drift in the iodine cell characteristics is then constant across all measured components. The innovations of the current setup of PDV will allow for simple integration of the technique into experimental rigs.

7. ACKNOWLEDGMENTS

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