De-rotation of a rotating channel flow using a stationary time-resolved PIV system

Shanying Zhang*, Firas Abdulsattar, Dennis Cooper and Hector Iacovides

School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester M13 9PL, UK
*corresponding author: shanying.zhang@manchester.ac.uk

Abstract This research deals with the challenges involved in the application of particle image velocimetry (PIV) techniques to the mapping of rotating flow fields. Such measurements usually rely on sophisticated and expensive hardware to synchronize the rotation and image frames obtained through fixed cameras, with a stationary laser beam produced outside the rotating platform. The alternative of having the entire PIV system on the rotating platform is rarely a practical option. With a camera also stationary outside the rotating table, a de-rotation procedure has to be carried out to remove the rotation of the frame to produce the true flow velocity, namely the fluid velocity relative to that of the rotating platform.
A new method is proposed to de-rotate the PIV images by only using the information available from the image itself. It involves a series of rotations and displacements of PIV images after identifying the instantaneous rotational speed of the rotating channel through the analysis of the PIV image time series. The proposed method has many advantages over other de-rotation procedures in several aspects, such as hardware requirements and final uncertainty. First, it only needs the PIV images, a few reference points and the reflection of the channel edge on the image to enable the de-rotation process. There is no requirement for extra hardware such as a synchronizer system. The variations of the rotational speed do not significantly affect the quality of the de-rotation results. This method is also robust to the effects of displacement of the centre of rotation.

Keywords: rotating flow, Particle image velocimetry.

1 Introduction

Rotating flow measurements have been explored extensively over the last few years, due to the importance of the rotational effects (Coriolis and, in non-isothermal cases, centrifugal forces) on the flow and thermal fields inside centrifugal impellers or cooling channels for gas turbine blades. PIV measurement is one of the very few common techniques used in this kind of investigation. The rotating flow can be measured either directly with all instrumentation sitting on the rotating platform, or indirectly with a stationary camera fixed outside of the rotating system.

The advantages of the direct measurement are a reduction in the measurement uncertainty and error related to the transformation from the absolute velocity to the velocity relative to that of the rotating system. Di Sante et al. [1] developed a facility consisting of a channel mounted on a 2.5 m diameter rotating disk together with a PIV system, which provides an uncertainty of 2% and is independent of the radial position or rotating speed. Visscher et al. [2] developed a 13m diameter turntable which could incorporate an 8m long duct and a stereoscopic PIV system for studying fully developed rotating channel flows. These high accuracy measurements of the relative flow come with a cost of sophisticated and expensive hardware, which is not widely available.

A popular indirect method, where a PIV system is fixed outside the rotating platform, uses a trigger signal to synchronize the PIV camera and laser at a certain location of the rotating channel for obtaining phase-lock measurements. This method usually suffers from many drawbacks in terms of error and uncertainty. Its uncertainty increases with rotational speed and the radial position of the measurements. Furthermore, at large circumferential velocities, the field of view of the stationary camera leads to a decreasing area. Accurate measurements in the boundary layer can be difficult. Armellini, et al. [3] quantified the uncertainty of the peripheral displacement field in the phase-locked PIV measurements on a rotating flow field. They concluded that an angle with maximum uncertainty of the order of 0.1% and the position of the centre of the rotation with an error in the range of 0.1 to1 pixels are necessary, for overall uncertainties to remain acceptable in the de-rotation process.

Modern synchronization systems can provide an accurate time separation between PIV images while the accuracy of the rotation speed heavily relies on hardware such as encoders and the test rig itself. The uncertainty should be evaluated based in the amplitude of the fluctuation of the rotation speed, not just the accuracy of the encoder. In some systems, the rotation speed itself can vary over 10% between different revolutions without careful control. Besides, the required accuracy of the rotation centre (0.1mm) from Armellini, et al. [3] is not easily achieved by a direct measurement considering the size of the rotation table. Furthermore, without a well-balanced load on the rotation table and with wear in the bearing system, the centre of rotation cannot be guaranteed to be in a fixed position for each and every revolution.

For all the above reasons, a new method is proposed to de-rotate the PIV images before a standard cross-correlation process can be performed to produce PIV velocity vectors. By only using the information available from the image series itself, the proposed method has no requirements on hardware such as a synchronizer for the rotational platform. Besides, this method is not affected by the variation of the rotation speed, and is also robust to dynamic displacements of the centre of rotation over the duration of each test. Finally, but no less important, the results show that induced uncertainty is negligible by the de-rotation process.

2. Experimental setup

The rotating water flow rig used here is at the Thermo-Fluids labs at the University of Manchester. A U-bend test section with a square cross-section of 50×50 mm and a length of 768mm has been mounted on the rotating platform. Operating conditions can go up to Reynolds number of 10^5 and rotation speed up to 250 rpm. Figure 1 shows the experimental setup for PIV measurements on the rotating platform, including laser light sheet and high speed camera (3.5 kHz) fixed outside the turntable. Detailed information can be found in Abdulsattar et al. [4]

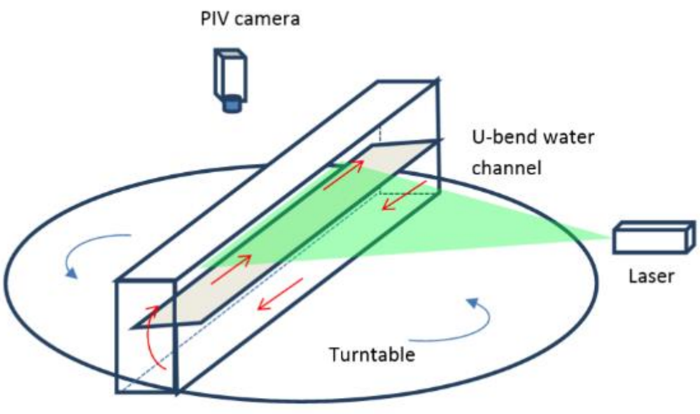


Figure 1. Experimental setup for PIV measurement

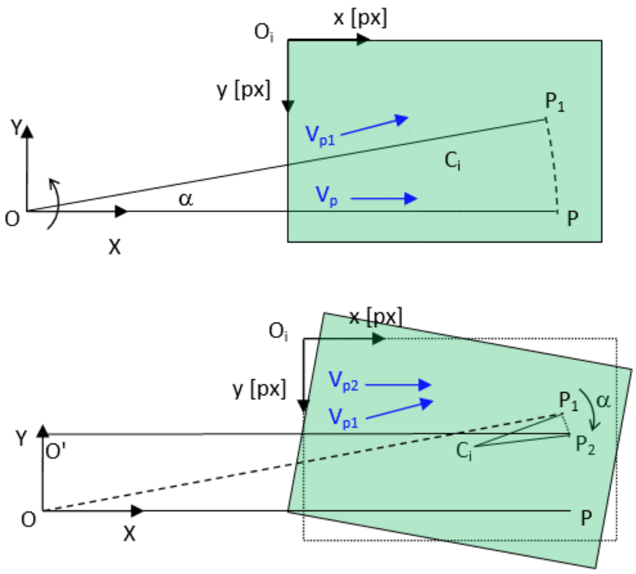
When the U-bend channel rotates with a stationary laser and also a stationary camera fixed outside of the rotating platform, the captured flow field through the camera includes the peripheral velocity component. The challenging problem is to remove the peripheral velocity to obtain the true fluid field velocity information relative to that of the rotating platform.

3. Method

Figure 2a shows the two coordinate systems involved in the investigation of a rotating flow using a stationary PIV system. The origin of the rotation platform (O) is the centre of the turntable and denotes the origin of the rotating coordinate system, while the origin (O_i) of image frame (in green colour) denotes the origin of the stationary coordinate system. The stationary origin (O_i) is located at the top left corner of the field of view (in green colour) of the PIV system. The centre of the PIV system field of view is denoted by C_i.

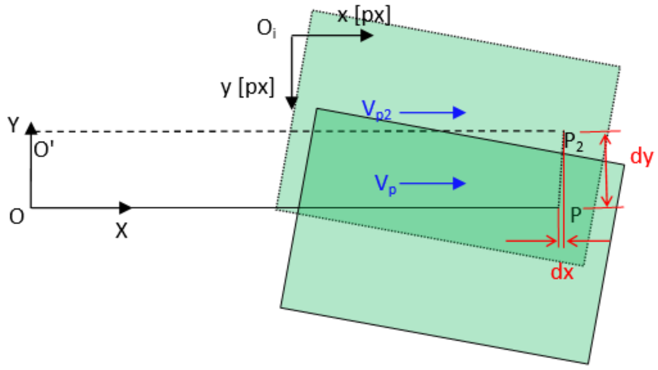
An arbitrary point **P** in a horizontal plane within the rotating channel illuminated by the laser light sheet is rotated to the point $\mathbf{P_1}$ around the centre of the rotation platform (O) by an angle α as shown in Figure 2(a). Consequently, a vector originally parallel to the x axis, V_P, is translated and also rotated by an angle α, to become V_{P1}. The aim of the de-rotation process is to transfer the point $\mathbf{P_1}$ back to its original location **P** and of course V_{P1} to V_P, through a series of transformations**.** The most common procedure is one simple step to rotate the point $\mathbf{P_1}$ back to its original point **P** by an angle equal and opposite to α, and a radius provided by the distance from the point P to the origin O. As described by Armellini, et al. [3], this method suffers from a series of drawbacks, such as harsh requirements for the accuracy of the angle and rotation centre position, and a complicated calibration process.

In contrast, the proposed de-rotation process can be divided into two stages. Firstly, the whole image frame is rotated at an angle α and in the direction opposite to that of rotation, around the centre of image ($\mathbf{C_i}$), rather than around the centre of the rotation platform, to bring the channel flow in a horizontal orientation as shown in Figure 2b. This moves point $\mathbf{P_1}$ to point $\mathbf{P_2}$ and the inclined orientation (OP_1) into horizontal line ($O'P_2$). As a result of this rotation, the vector V_{P1} is transformed to V_{P2} which is again aligned with the x direction. Comparing with the methods of rotating around the centre of the turntable, this transformation will reduce the uncertainty induced at various radial locations where the field of interest may lie. Because a larger uncertainty will be induced at a larger radial position in terms of the absolute displacement for the same uncertainty of the rotational speed. The reason to choose the centre of the image as the centre of rotation is to keep the area loss caused by the rotation to the minimum as revealed from Figure 2b. After this rotation, the second step is to translate the whole image to move point $\mathbf{P_2}$ back to point **P** and horizontal line ($O'P_2$) return to line (OP) to complete the de-rotation process as shown in Figure 2c. A consequence of this second transformation is the translation of vector V_{P2} back to the original location of V_P. Detailed procedure and analysis are explained in the following sections.



(a)

(b)



(c)

Figure 2. Diagram of the de-rotation procedure (a) Peripheral coordinate system (*O*) and the image frame system (O_i); (b) Image rotation around the centre of image C_i; (b) Image shift (*dx*, *dy*)

3.1 The estimation of rotation angles

In most studies of rotating flows, estimations of the rotation angle rely heavily on hardware such as encoders and counters which do not take into account the fluctuations of the rotating platform. In the proposed method, the image processing techniques have been used to accurately estimate the rotation angle without any effects on accuracy from variations in rotational speed, or uncertainties in the location of the platform centre of rotation.

Firstly, the correct rotational angle α is estimated for each of the image frames in relation to a reference horizontal or vertical image frame. This enables image frames to be de-rotated into a suitable orientation, such as horizontal or vertical, for further analysis. The reflection of the laser light sheet on the straight side walls of the channel, as indicated in Figure 3, can be used as a fixed feature, to estimate the angle of the rotating channel relative to the reference direction.

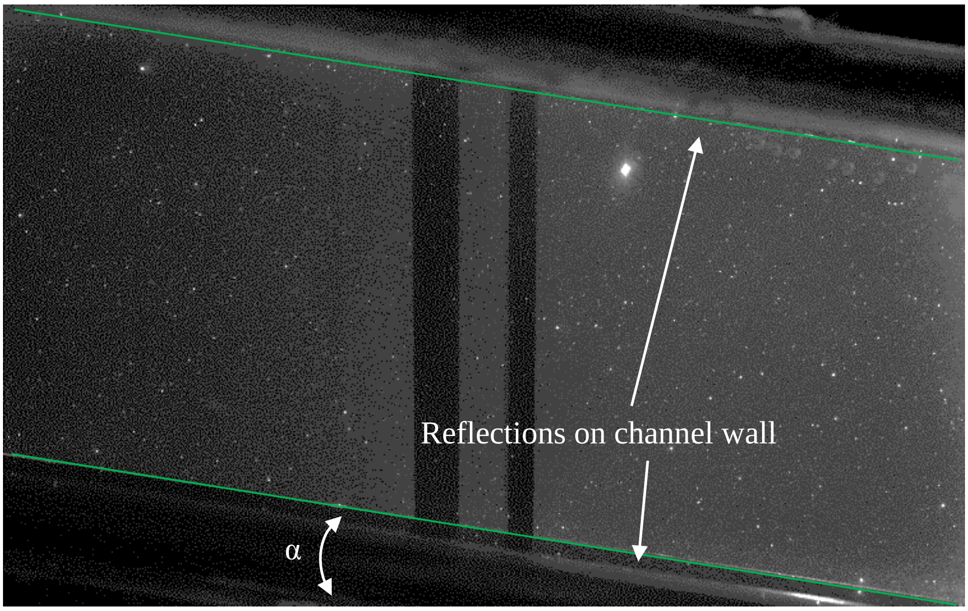


Figure 3. PIV image of a rotated channel

The radon transform is a well-defined linear feature detector and it is less sensitive to the noise in the image than other methods, such as a rough transform, since noise tends to be cancelled out by the integration process.

Zhang and Couloigner [5] proposed a modified radon transform, which uses a profile-based technique to detect accurately the centreline of the thick line in the images. The method enables the angle of a thick reflection line (e.g. in Figure 4a) on the side of the channel to be estimated accurately for each image frame.

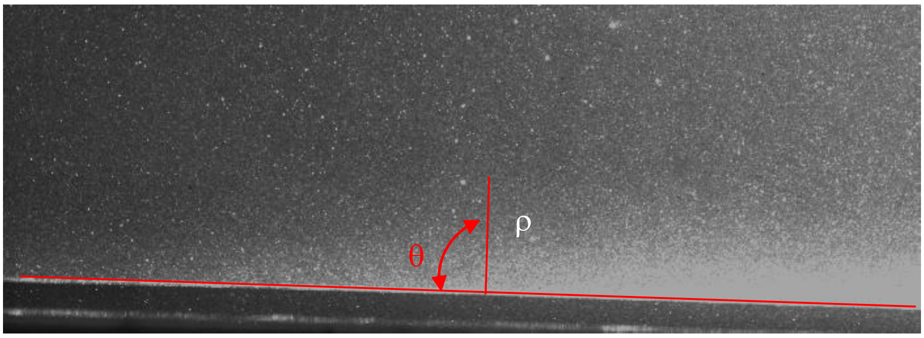
The Radon transform of the greyscale image *I(x,y)* (e.g. Figure 4a) for angle θ is the projection of the image intensity along a radial line oriented at an angle of θ with an offset ρ as shown in following equation

$$R(\rho,\theta) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y)\delta(\rho - x\cos\theta - y\sin\theta)\,dxdy$$

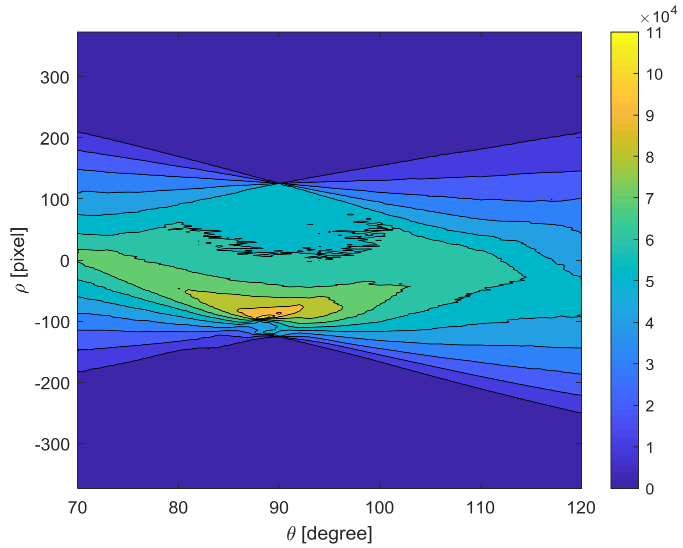
where $\delta(.)$ is the Dirac delta function

$$\delta(z) = \begin{cases} +\infty, & z = 0 \\ 0, & z \neq 0 \end{cases}$$

So $\delta(\rho - x\cos\theta - y\sin\theta)$ term forces the integration of *I(x,y)* along the line defined by $\rho = x\cos\theta + y\sin\theta$.



(a)



(b)

Figure 4. Sample of radon transform (a) original image (b) radon image $R(\rho,\theta)$.

The result is a new image of contour $R(\rho,\theta)$ as shown in Figure 4b, where ρ is the distance in pixels from the centre of the image to the projection line $\rho = x\cos\theta + y\sin\theta$, where the integration is forced to occur.

The angle between the reflection line in Figure 4a and the vertical direction can be obtained as the angle θ from the radon peak on the image R(ρ,θ) since the line integration reaches the maximum when its position falls on the bright reflection line as indicated by the red line in Figure 4a. In this case, the inclined angle of the line is 89 degree from the vertical.

To obtain a good resolution of the angle estimation and with reasonable computing costs, two stages of radon transforms are used. The first radon transform uses angles in a wider range (e.g. θ from 70 to 120 degree) with a spacing of 1 degree as shown in Figure 4. From this, a true radon peak (θ = 89) will be produced corresponding to the inclined angle of the channel with a resolution of 1 degree. The next radon transform uses angles in a narrower range (e.g. 4 degree) around the angle (in this case θ = 89) obtained from the first radon transform with a much fine spacing of 0.002 degree. This enables the angle of the oblique channel to be estimated with a higher resolution of 0.002 degree. A series of angles θ_i (i = 1…N) are obtained from the radon transforms of the time resolved PIV images from the first images of the PIV image pairs using a standard Matlab function *radon*. With an assumption of constant or linear speed variation in the narrow swept area of less than 10 degrees, a linear model can be created to improve the accuracy of the local rotation angles further, and also to remove scatter data as indicated by the blue set of data in Figure 5. It is thus more reliable to obtain the local instantaneous rotational speed, *ω*, as the slope ($\Delta\theta/\Delta t$) of the linear model in red colour in Figure 5.

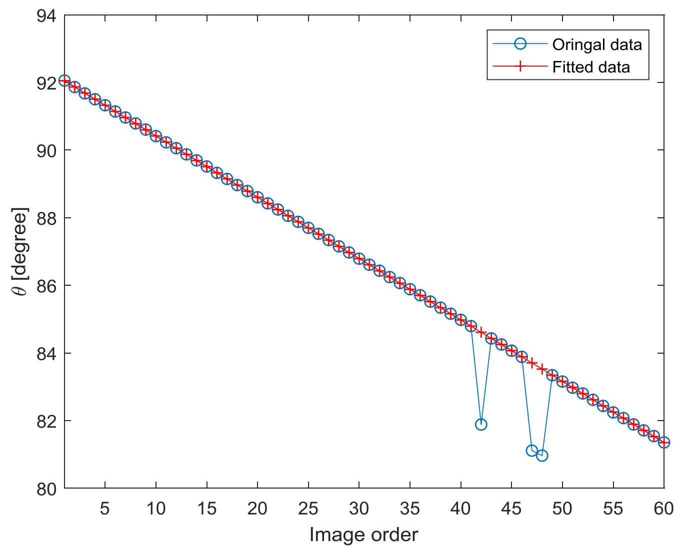


Figure 5 A linear model of the rotating angles used to remove scatter data in blue

To improve the quality of the images for the radon transformation, several image processing methods are implemented before the radon transformation, and the PIV image is cropped into a small area as shown in Figure 4a, which includes only a reflection line feature. Since more than one line feature could make Radon peak finding difficult and inconsistent. For PIV images with strong reflections on the side channel, images are converted into binary ones to prevent the bias caused by the uneven reflections. This is achieved by a standard Matlab function *im2bw*. Then, a filter function *bwareaopen* is used to remove bright spots produced by the PIV seeding particles from the binary image. This is used to reduce their influence on the result of the radon transformation. In some situations, reflections of the laser light sheet on the side walls are too weak to easily separate those from the background and those caused by seeding particles. Intensity capping, which is commonly used in PIV pre-processing [6], can help to reduce the interference of bright seeding particles on the radon transform.

For PIV cross-correlation, it is crucial to estimate the rotation angle of the second frame of a PIV image pair. Although the above procedure can be repeated for the second image frame series illuminated by the second laser pulses, the uncertainty induced from different laser light sheets and exposure timing could affect the accuracy. Therefore an indirect method has been used. With the rotation angle θ of the first frame of a PIV image pair, the rotation angle can be easily obtained for the second frame as $\theta + \omega\Delta t$, where ω is the local instantaneous rotation speed obtained by the linear model of the rotation angle data and Δt time separation between the PIV image pairs, which is defined by the PIV system.

To rotate the image frames, several interpolation schemes can be used. Astarita and Cardone (2005) examined the influence of the interpolation schemes on the accuracy of the PIV algorithm, and concluded that the bi-cubic method should be used to obtain a good compromise between speed and accuracy. If the accuracy is the only concern, other schemes can also be used.

3.2 Determination of displacement of the image frames

Following the rotation of the PIV images into a horizontal orientation, the horizontal and vertical displacements (*dx, dy*) need to be estimated accurately to move the point $\boldsymbol{P_2}$ back to the position *P* as shown in Figure 2c. This is achieved through a two-step cross-correlation [7] of a sub area in the rotated PIV images, which includes a fixed reference feature such as special reflection points on the edge as indicated by the thick black line shown in Figure 6a. The locations of these features on the channel are fixed and are not affected by the small angle of the rotation of the platform and are located within the stationary light sheet. Figure 6a shows that the first cross-correction is carried out over a relatively larger area, such as 400x100 pixels, of PIV image frames A and B, to generate an estimation of the displacements (*dx, dy*), in the horizontal and vertical directions. Then, a sub-pixel accuracy of the estimations is achieved by using an offset correlation, where first offsets frame A in (*dx, dy*) to frame A', then cross-correlates between A' and B as shown in Figure 6b, on a smaller area, such as 50x20 pixels, with a feature that is not affected by rotation. After displacements are estimated with the two-step cross-correlation process, these data will go through a filtering process, which is the same as the linear model in the previous section, to remove bad displacement data and to replace them with a new data.

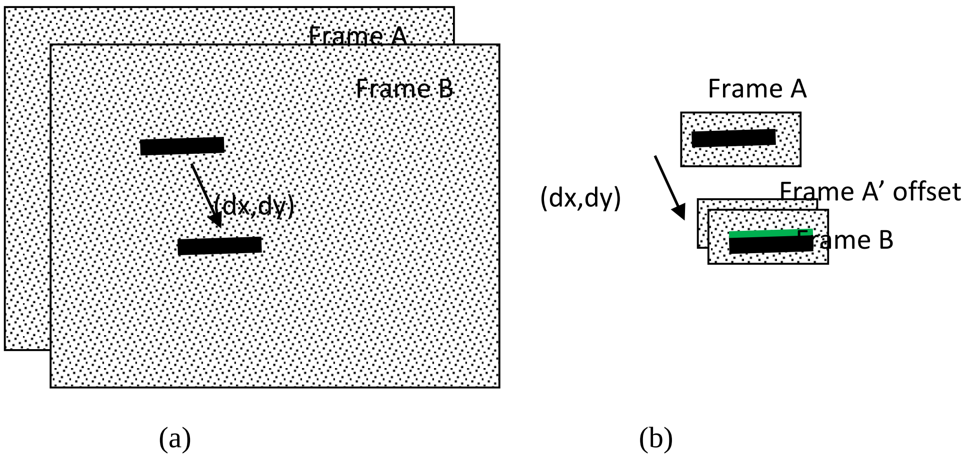


Figure 6. Two step cross-correlation. (a) cross-correlation; (b) offset cross-correlation.

Theoretically, the obtained displacements have a close relationship with the rotation angle. This relationship can be calculated with a known centre of the image and rotational angle. Figure 7 shows the variations of normalised horizontal and vertical displacements (*dx, dy*) with rotation angles for four PIV image series with different distances from image centre to centre of rotation (OC_i = 50, 500, 2000 and 5000 pixels). It is can be seen that the vertical displacement increases linearly with the rotation angle while the profile of the horizontal displacement shows a parabolic variation with the minimum (0) value at the zero angle. It is noticed that the green line (OC_i = 50) is not in line with other parabolic curves in Figure 7a. The reason is that the shape of the parabolic curve is changed due to the larger horizontal displacement when the image centre is close to the centre of rotation. To improve the accuracy of the estimation further, first and second order linear regression models are created, based on measured vertical and horizontal displacement data respectively. These models are used for the prediction of the vertical and horizontal displacements respectively, to remove the scattered and unreliable data.

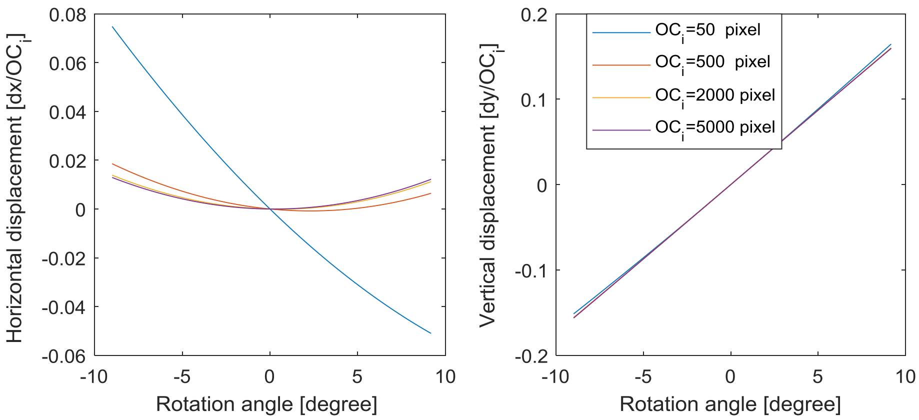


Figure 7.Variations of the horizontal and vertical displacement (*dx*, *dy*) from point P_2 back to P for different rotation angles for four positions of image frames.

Since the cross-correlation is used in both estimations of the displacement for the current de-rotation procedure and PIV measurements, any small error in the de-rotation process will cause larger errors in the final PIV results. To prevent large errors being induced by moving the second frame of the PIV image pairs, the linear model between rotational angle and the displacement is used to predict the displacement (*dx*, *dy*) from the first frame of the PIV image pairs by interpolating with a known rotation angle of $\theta + \omega\Delta t$ for the second frame, which is accurately calculated from the first part of the procedure.

4. Example

Figure 8a shows a superimposed image which includes a sequence of four PIV images with a time separation of 10.2ms. It is seen that the inclined channel walls indicate that the channel flow sweeps through the field of view of the PIV camera clockwise, and the centre of the rotation is on the left of the image. Many groups of bubbles appear in the superimposed images that follow the main flow from left to right. The radon transformation is applied to the top half of each image including the bright reflection edge to estimate the angle between the edge and the vertical direction for each PIV image frame. Using this sequence of angles, PIV images can be rotated around the image centre to the horizontal orientation, as shown in Figure 8b. Using the fixed reflection feature as indicated in the red circle in Figure 8b, the two step cross-correlation is implemented to find the displacements in the vertical and horizontal directions (*dx*, *dy*), then images are shifted to make the fixed channel walls overlap onto one line for every frame. The final four de-rotated image frames are superimposed together as shown in Figure 3(c). It can be seen that the de-rotation is very successful with a single instance of the channel edges in the superimposed image. After the de-rotation process, a normal PIV realisation can be implemented.

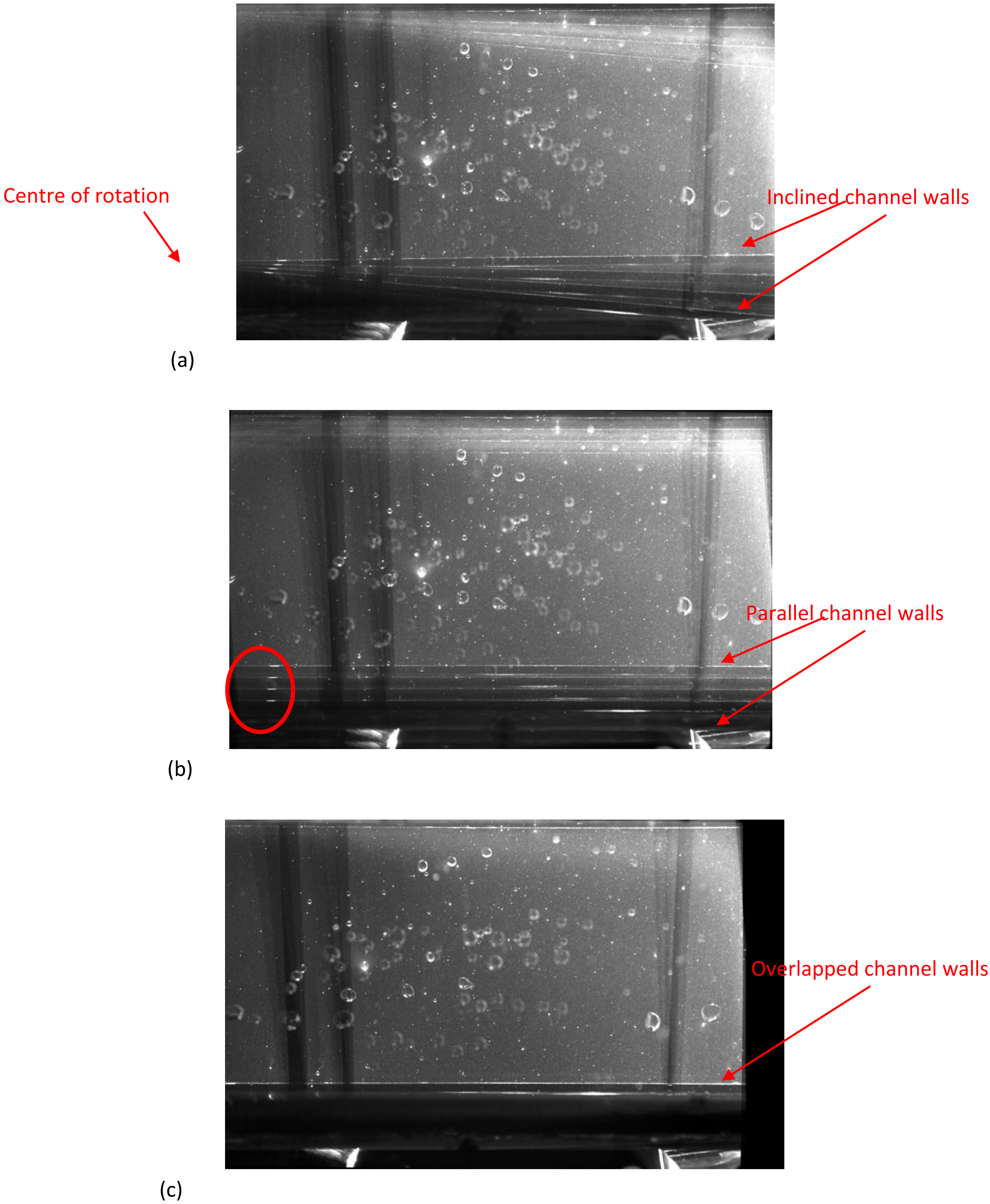


Figure 8. De-rotation procedure for PIV images. (a) 4 PIV frames; (b) 4 rotated image frames; (c) 4 displaced image frames

5. Concluding Remarks

A new de-rotation procedure has been proposed for PIV measurements of rotating channel flows. It is composed of two steps: The first step is to rotate the PIV images around their centres into a reference orientation, such as vertical or horizontal. The second step is to translate the rotated image back to original position of the reference channel. To make this method successful, a profile-based radon transform is used to accurately estimate the inclined angle of the channel and a linear regression model was used to filter scattered data and improve its accuracy. The displacements in the vertical and horizontal directions are estimated using offset cross-correlation before the linear regression models are implemented for two displacements to remove scatter data and improve accuracy.

Compared to previous de-rotation methods, this method does not have major and expensive hardware requirements in order to determine the rotation angle, and its accuracy is not affected by fluctuations in either the speed of rotation, or the location of the centre of rotation.

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