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Improving the dynamic range of particle tracking velocimetry systems

W. L. Lim, Y. T. Chew, T. C. Chew, H. T. Low

Abstract In applying a video-based particle image velocimetry (PTV) system in a complex fluid flow, it is common to find both regions of fast and slow moving flow intermixing–particularly in highly turbulent or reversing flows. When one attempts to track the movement of particles in such a flow with a wide velocity range (and hence, separation distance between particle images), resolution problems are encountered. Inability to cover a wide range of velocities is actually a limitation of PTV. A method is introduced here that extends the dynamic range of PTV when implemented on a video-based system. It combines the use of multiple frames and multiple exposures on a single frame. The method is subsequently verified by tracking dots painted on a spinning flat disc.

1 Introduction

Particle tracking velocimetry (PTV) is a method whereby the instantaneous fluid velocities of a flow field are determined by measuring the displacements of particles in the seeded flow. The method involves illuminating a particle laden flow with a uniform sheet of light and capturing the images of the flow on film or video. These images are analysed to obtain the particle velocities by determining the particle displacements over a known time interval.

In PTV, the quality of measurement of flow displacements is dependent on a number of factors. Firstly, the framing rate of the camera (in terms of frames per second) limits the measurable velocity range. If the framing rate is too low, a particle travelling at a high velocity may have left the illuminated field of vision of a captured image. Methods of coding the movement of particles in a single frame have been employed by pulsing the light sheet such that the displacement of the fast-moving particles may be visible in a single frame (Adrian (1991)). However, this method of pulse tagging fails in tracking slow-moving particles, where the particle streak in a single frame does not warrant it to be coded visibly. So, one either has to zoom in to this region or change the pulse tag. Grant and Liu (1990) employed different pulse tagging on photographic film to overcome this problem but did not address the problem when encountering flow with a wide dynamic range on a single image. Secondly, tracking both fast and slow-moving particles simultaneously on a single image poses problems on the accuracy of the spatial resolution of the measured particle displacement. Magnifying the image in terms of 'zooming' into the slow moving particles region to improve the resolution of the slow-moving particles' displacements may lead to ambiguity in tracking the coded fast-moving particles. This ambiguity arises from the fact that most PTV routines track particle movement by distance based criteria – the particle moves minimally in a specified time interval such that particle pairing is possible. On the other hand, zooming out of the flow field results in data inaccuracy in the slow-moving region.

In a complex fluid flow, one can usually find both regions of fast and slow moving flow intermixing – particularly in highly turbulent, rotational or reversing flows. When one attempts to track particles with a wide velocity field range, images of both fast and slow-moving particles on a single image are not properly spaced to be tracked. Even when the image is pulse tagged, there are particle spots that overlap due to the slow-moving velocity. Inability to cover a wide range of velocities is actually a limitation of PTV. This paper is an extension of the work done by Lim et al. (1991, 1992) and serves to introduce a method that extends the dynamic range of PTV when implemented on a video based system.

2 Experimental method

The method is based on the fact that the flow field is captured on video, thus providing images as a function of space and time instead of using photographic film which provides resolution only in space. By using the space function, one may pulse tag the fast-moving particles in a single frame. This is performed when the particle is travelling at a high speed such that they cannot be tracked in successive frames as they would have left the image field. The pulse tag determines the direction of motion of the particle and also provides a check for particles which enter or leave the light sheet during the camera exposure.

For slow-moving particles where the pulse tag may not be distinguishable, the time function is utilised. The particles in this region may be tracked by successive frames, thus providing a large distance travelled by the particle. The particle movement for this region may also be tagged just by analysing a sequence of selected frames. Thus by choosing frames 1, 5, and 7, we obtain a 2 to 1 ratio tag.

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W. L. Lim, Y. T. Chew, T. C. Chew, H. T. Low
Department of Mechanical and Production Engineering, National University of Singapore, Kent Ridge, Singapore 0511

Correspondence to: T. C. Chew

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Apparatus

An experiment was carried out to test the accuracy of the measuring method. A flat metal disc with particle markers on the surface was rotated at a specific speed. The markers were illuminated by a continuous wave laser spot pulsed by a mechanical chopper to obtain a stroboscopic effect. The mechanical chopper produces pulses with different duration and different separation times. The images were recorded on video and grabbed into an IBM compatible PC computer a single frame at a time. This was performed by video cassette recorders with jog and shuttle functions. The video images were stored in a 512 by 512 pixel configuration and the light intensity of each pixel was represented by one of 256 grey levels.

4
Image processing techniques

The images were processed in two steps. First, a single captured and stored image was obtained and the locations of the tagging spots and their centroids computed. Figure 1a shows a raw single frame PTV image where the light source is pulsed at a 2:1 ratio. The overlapping spots near the centre of the spinning disc (top right hand corner of Fig. 1a in dotted window) corresponds to slower moving particles. The fast moving particles (enclosed in a window in Fig. 1a) were initially tracked by using the pulse tagging criteria. The particles were matched when they satisfied the pulse ratio. Velocity vectors were inferred from the measured displacements (Fig. 1b).

The next step was to analyse the slow-moving particles. The required frames over time to satisfy the pulse tag ratio were obtained and analysed using the same criteria as the fast-moving particles. For instance, using frames (1, 3, 4), (1, 5, 7), etc. Figure 1c shows the summation of the frame shown in Fig. 1a and the third and fourth frame after it. Only the slow moving particles (the region corresponding to the dotted window in Fig. 1a) were analysed while the fast moving ones were ignored. This is performed by windowing into the selected region to analyse. Thus if a particle is travelling very slowly, one just needs to choose frames with larger time intervals where the motion of the particle is sufficiently large to be measured accurately. The

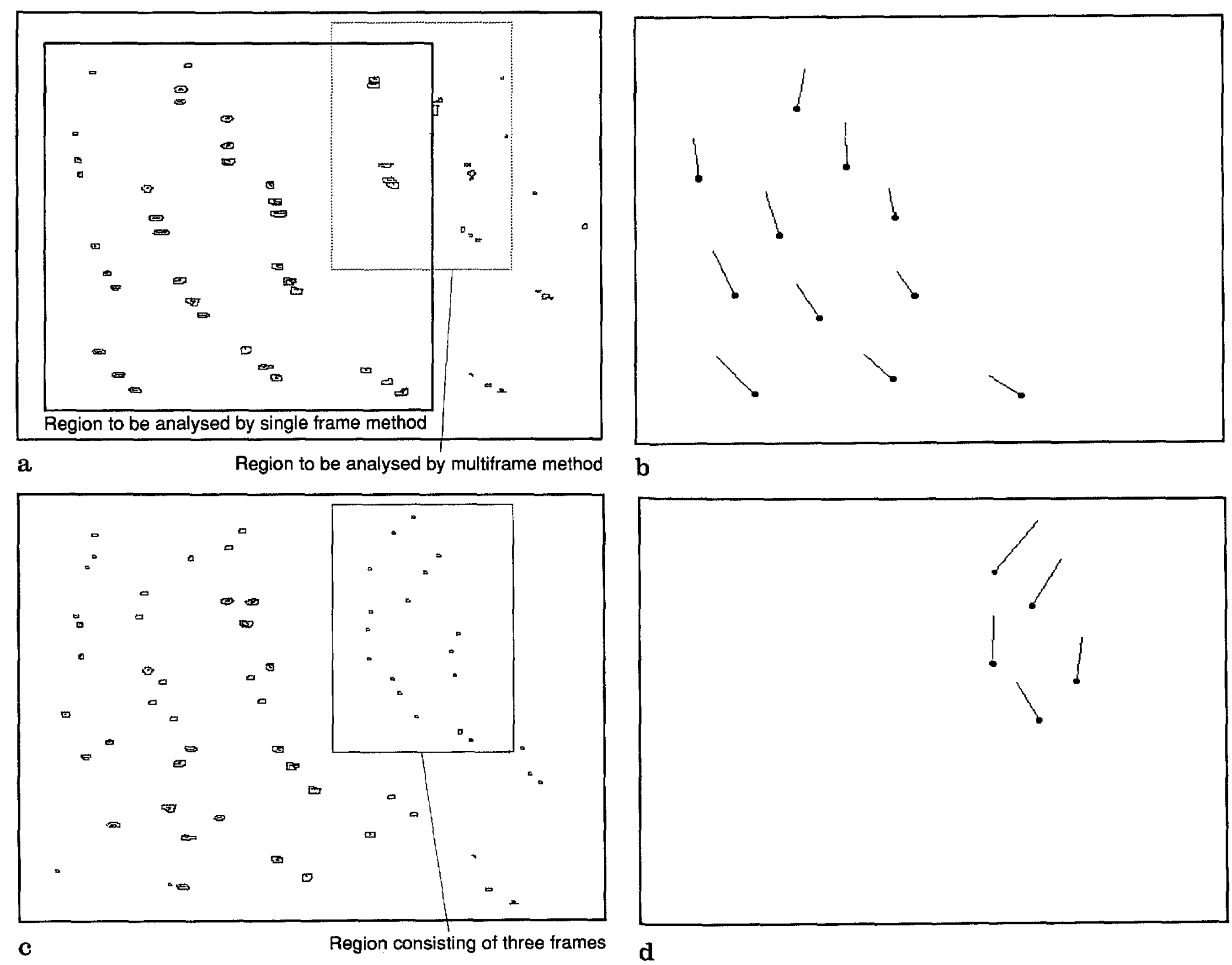

Fig. 1. **a** Raw single frame PTV image of spinning disc with pulsed light sheet at 2:1 ratio; **b** Velocity vectors inferred from Fig. 1a of fast moving particles with the single frame method; **c** The resultant addition of the image frame in Fig. 1a and the third and fourth frame after it; **d** Velocity vectors inferred from Fig. 1c of slow moving particles with successive frames

direction of motion was obtained by resolving the frame sequence and the velocity vectors inferred (Fig. 1d).

5 Discussion

The PTV velocities obtained were compared to the theoretical velocity distribution of the spinning flat disc. Figure 2 shows the velocity distribution obtained by both single-frame and multi-frame technique against radial plot of the spinning disc with its corresponding theoretical plot and error percentages. The dynamic range ratio is of the order of 13 (by simple ratio of the highest and lowest velocity measured). At very low velocities (near the disc centre), velocity vectors were not obtained as the trajectory traversed by the markers could no longer be approximated by a straight line; they were travelling in an arc. However, this is an artificial limitation introduced by the verification method chosen. In practice, error due to curvature may not be present for slow moving particles, and the dynamic range can be pulsed higher. From Fig. 2, it is also observed that at higher velocities, the PTV results show considerable scatter. However, we are certain that much of this scatter is due to uncertainties unrelated to the PTV scheme. In order to confirm this, image frames were randomly sampled. Visual inspection confirmed that the particle location and displacement have been correctly deduced by the PTV scheme. The rotational speed of the disk can only be controlled to 2%, and that of the laser beam mechanical chopper to 1%, thus explaining part of the errors discerned. This is due to the error in determining the pulse tag time interval of the mechanical chopper. Though the chopper can be accurately marked the rotational speed produced by the motor may not be accurately determined by a tachometer. However, at low velocities, using the multiframe method, the time interval can be accurately determined as it is fixed by the camera framing rate and hence a lower scatter is observed. The error distribution was found to be well within 12% of theoretical values (Fig. 2). However, taking into account the errors introduced by the chopper and the rotating disk, we are confident that the error distribution for the PTV scheme will fall within 5% or lower.

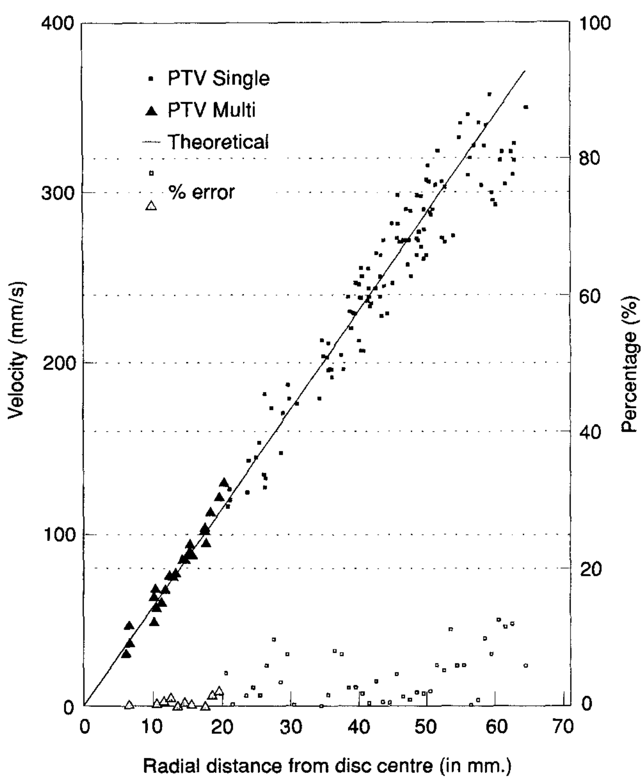

Fig. 2. Velocity distribution against radial distance from disk centre at 55 rpm

In actual measurements in fluids, an additional challenge would be to measure both slow and fast vectors within the same region. This will be done by first finding the fast vectors by light sheet pulsing. The images that have been matched are removed from the frame. Successive frames are then used for finding a match to the remaining particle images in the initial frame for the slow vectors.

6 Conclusion

In this work, the method of increasing the dynamic range of PTV by using a double method of analysing PTV images – single frame pulse tagging of fast-moving particles, multiframe tracking of slow-moving particles – was found to be a viable tool to study turbulent flow conditions with a wide dynamic range of velocity at an accuracy comparable to single-point measurement methods.

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