Spatial Resolution Enhancement of PIV Velocity Field using Optical Flow

Jee Hyun Seong[1,2], Min Seop Song[1], Daniel Nunez[3], Annalisa Manera[3], Eung Soo Kim[1]*

[1]*Department of Nuclear Engineering, Seoul National University, 559 Gwanak-ro, Gwanak-gu, Seoul, South Korea*
[2]*Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.*
[3]*University of Michigan, Ann Arbor, Michigan, U.S.*

E-mail: kes7741@snu.ac.kr

1. Introduction

Particle image velocimetry (PIV) is a widely-used flow visualization technique that can measure the velocity components of two- or three-dimensional fields through the successive image pairs of tracer particles in the flow field. PIV enables us to work out not only the qualitative form of the flow but also the quantitative hydrodynamic characteristics at the same time. For this reason, this measurement technique is being actively used for fundamental research in the field of nuclear thermal-hydraulics.

For decades, efforts have been devoted to address the challenges and increase the resolution of correlation-based PIV. High-speed cameras and high-repetition lasers reduce the interframe time and high-resolution cameras enhance the spatial resolution [1][2]. The iterative multigrid approach, multi-scale iterative image deformation, and the single-pixel resolution ensemble approach have been adopted to refine the size of the interrogation areas and increase the spatial resolution of the correlation methods [3][4].

In this study, a novel method of reprocessing the particle image pairs using the optical flow technique is proposed to improve the spatial resolution of the velocity vectors obtained by conventional PIV. In the new method, the particle image pairs are first processed using the correlation-based PIV method and then one image is transformed based on the PIV velocity field. Then, the optical flow technique is applied to refine the velocity vectors. The details of the method and the results are described in the following sections.

2. Method

In this study, optical flow analysis has been used for enhancing PIV velocity spatial resolution. The optical flow analysis has been first proposed for object detection in computer vision, and it analyzes the variations in pixel intensities over time of successive image pairs to obtain the velocity vectors [5]. Since the optical flow analyzes the velocity field through the intensity change in the pixel, one velocity vector can be obtained per pixel theoretically.

2.1. Basic Theory of Optical Flow

Optical flow methods calculate the motion between two sequential images taken at time t and t+dt at every pixel position. When I(x, y, t) is the intensity of the image obtained at time t, and the position (x, y, t) is moved by dx, dy, and dt between the two images, the intensity of these two point can generally be assumed to be identical [5].

$$\mathrm{I(x,y,z) \approx I(x+dx, y+dy, t+dt)} \qquad (1)$$

The right hand side of Eq. (1) can be expanded using the Taylor series. Then, the following basic optical flow equation can be obtained.

$$\mathrm{I_x u + I_y v + I_t = 0} \qquad (2)$$

where, $\mathrm{u = \frac{dx}{dt}, v = \frac{dy}{dt}, I_x = \frac{\partial I}{\partial x}, I_y = \frac{\partial I}{\partial y}}$, and $\mathrm{I_t = \frac{\partial I}{\partial t}}$.

However, Eq. (2) has two unknown variables (u, v) (*aperture problem*) and, therefore, an additional equation is necessary to c lose the equation. Depending on how the constraint is provided, the methods are grouped into two categories: a local method first proposed by Lucas-Kanade and a global method pioneered by Horn-Schunk [5]. In this study, we used a global optical flow method following the recent studies on the optical flow application to PIV [6][7]. In this global optical flow method, smoothness assumption is generally adopted to prevent outliers (Horn-Schunk 1981; Brox et al. 2004).

In this study, we added the *brightness gradient constancy* assumption proposed by Uras et al. (1988) and Brox et al. (2004). This method is reported to improve the result more reliable and robust than the original [8]. The *brightness gradient constancy* assumption is expressed as follows.

$$\mathrm{\nabla I(x+dx, y+dy, t+dt) \approx \nabla I(x,y,t)} \qquad (3)$$

By applying the second-degree Taylor expansion, the following equations can be obtained from Eq. (3)

$$I_{xx}u + I_{xy}v + I_{xt} = 0 \qquad (4)$$

$$I_{xy}u + I_{yy}v + I_{yt} = 0 \qquad (5)$$

In addition, L1 penalization, $\psi(s^2) = \sqrt{s^2+\epsilon^2}$ was adopted to achieve better stability and convergence [8]. The final equation sets are as follows.

$$E_{total} = E_{data} + \alpha E_{smoothness} \quad (6)$$

$$E_{data} = \int \psi\left((I_x u + I_y v + I_t)^2 + \gamma\left((I_{xx} u + I_{xy} v + I_{xt})^2 + (I_{xy} u + I_{yy} v + I_{yt})^2\right)\right) dxdy \quad (7)$$

$$E_{smoothness} = \int \psi(|\nabla u|^2 + |\nabla v|^2)\, dxdy \quad (8)$$

2.2. Velocity Enhancement Algorithm

Fig. 1 shows the basic algorithm to enhance PIV velocity field using optical flow. First, displacement and velocity fields (u, v) are obtained from two successive images (Image-1, Image-2) using conventional PIV analysis. Then, one of the images (Image-2 in Fig. 1) is transformed into a new image (Image-2C) by the reverse amount of the obtained velocity field (-u', -v'). By this process, Image-2 becomes close to Image-1 but not perfectly matched. To reduce this deviation, the optical flow is applied pixel-by-pixel for Image-1 and Image-2C. With this analysis, the velocity deviation field (du, dv) is obtained. Finally, the PIV velocity field (u, v) and the optical flow velocity field (du, dv) are added to obtain the final velocity field.

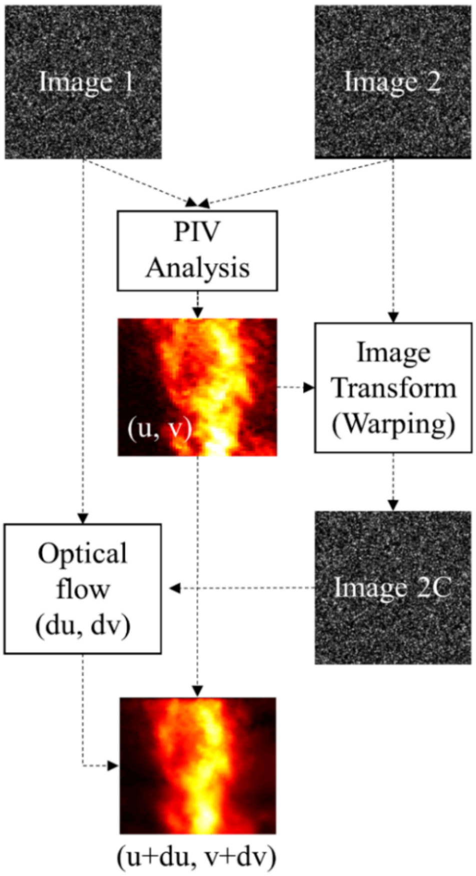

Fig. 1 Velocity enhancement alorithm

3. Results and Discussions

3.1. Application to synthetic image pairs

The proposed method was applied to a synthetic particle image sequence generated from the direct numerical simulation (DNS) velocity dataset of turbulent flow with Reynolds number (Re) of 3000, Schmidt number (Sc) of 0.7, Péclet number (Pe) of 2100, and the time step of 0.01 [10]. The synthetic particle image and the exact velocity field are shown in Fig. 2 (a) and (b). As shown in Fig. 2 (c) and (d), the proposed method well resolved the PIV velocity field and the analysis results show clear turbulent features.

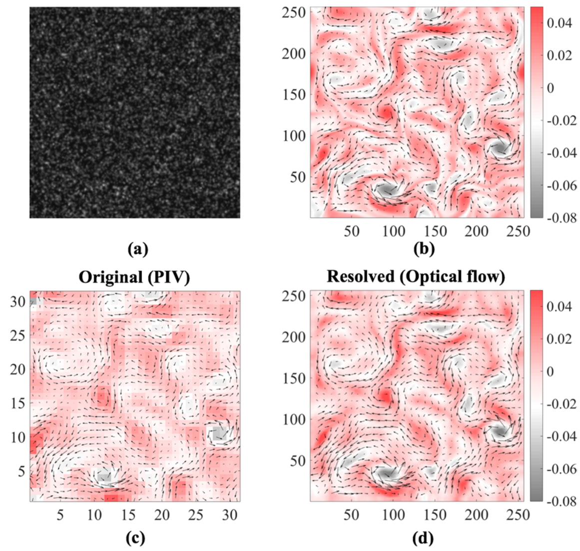

Fig. 2 Analysis on synthetic image pairs. (a) Synthetic particle image (256×256 pixel^2; not-to-scale); (b) Reference DNS velocity field; (c) original PIV (31×31 pixel^2) and (d) resolved (256×256 pixel^2)

3.2. Application to real image pairs

In this section, the proposed method was applied and tested on the real experimental data. Experiments were conducted on the multiple rectangular jet flow in the Reactor Cavity Cooling Systems (RCCS) separate-effects test facility, built in the Experimental and Computational Multiphase Flow (ECMF) laboratory at the University of Michigan. PIV particle image pairs were obtained in six parallel rectangular jets, with jet Reynolds number of 1.38×10^4. For these measurements, a 532 nm Nd:YAG laser and a 12MP CMOS camera with a sensor size of 4096×3072 pixel^2 and pixel size of 5.5×5.5 µm^2 were used.

Fig. 3 (a) and (b) show the instantaneous velocity magnitude fields obtained by the PIV and the proposed method, respectively. The x-axis and the y-axis were scaled by the width of the rectangular jets, L_1=12.7mm. In addition, small sections of the velocity vector fields, constituting of the velocities in the x and y directions, are provided in Fig. 9 (c) and (d).

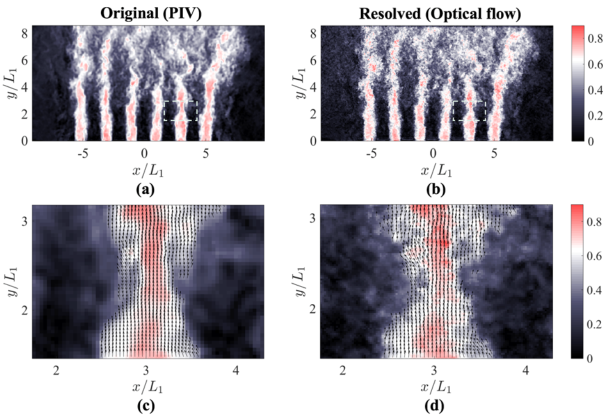

Fig. 3 Analysis on multiple rectangular jets in the RCCS facility. (a)(c) original PIV (435×215 pixel^2) and (b)(d) enhanced (870×430 pixel^2).

As shown in Fig. 4, the streamwise velocity fields obtained by the two methods show very good agreement in general, and the original velocity vectors are well resolved by the proposed method which increased the resolution by a factor of two.

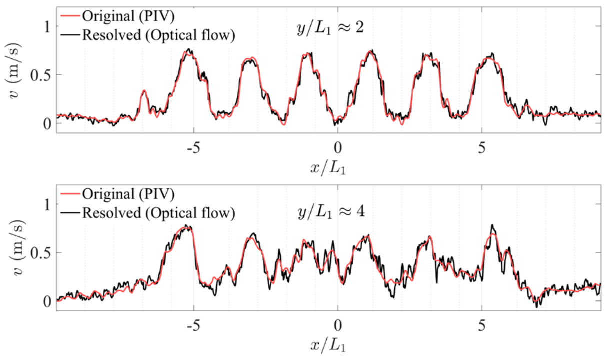

Fig. 4 Instantaneous streamwise velocity profiles at two different y/L_1 axial locations

4. Conclusions

In this study, a method to enhance spatial resolution of PIV velocity fields by optical flow post-processing. The brightness gradient constancy assumption is employed to ensure robust estimation under brightness variation depending on the PIV set-up and synchronization of a laser and a camera. The proposed method was evaluated on synthetic and real image pairs and demonstrated to refine the PIV velocity field successfully. Since the existing optical flow is susceptible to experimental noise and imaging conditions, particle images should be properly prepared, e.g., with relatively small particle displacement. Whereas the proposed method reduces particle motion to small scale displacement by mapping one image to the other using the coarser, correlation-based output prior to the optical flow analysis. Hence either large displacement or curvilinear motion of particles, which are often considered as limiting conditions in optical flow applications, can be processed as a linear with a relatively small-scale. The applicability of the proposed method is not only limited to single-phase flow but potentially can be extended to two-phase flow.

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