SMART IMAGE PROCESSING OF FLOW VISUALIZATION

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ABSTRACT

The purpose of this study is to develop an application of the smart visualized image processing to turbulent flow images and PIV (Particle Image Velocimetry) technique in order to improve the temporal resolution of images. Flow images consist of a set of sequentially discretized images in time domain. The smart visualized image processing can convert the discretized images into continuous images based on Helmholtz equation. In this paper the turbulent wake images and standard PIV images were used to evaluate the smart visualized information processing. Images of a turbulent wake with higher temporal resolution were generated, which were used to analyze the mechanism of wake flow. The PIV results obtained from the generated PIV images agreed with the accurate solution. One can say that the smart visualized image processing technique is effective in both flow image analysis and PIV system.

INTRODUCTION

The flow visualization technique, such as image processing [1] and Particle Image Velocimetry (PIV) [2], can provide qualitative and quantitative information on flow field. It has the unique ability to capture instantaneous full-field flow and thus to allow the detection of spatial structures in unsteady flows. In general, the flow visualization technique flow is divided into two processes: image recording and analysis. The recorded images consist of a set of sequentially discretized images in time domain, and the evaluation of a flow visualization technique is often characterized by its temporal and spatial resolutions of images. Much progress in hardware has been made for improving the spatial and temporal resolutions, however, the temporal resolution is still a problem to be solved since the recording speed of CCD cameras is limited. Therefore it is important to develop software for increasing the temporal resolution of image. Recently, Saito [3] developed a new visualization technique, called the "smart visualized information processing". This technique can convert the discretized images into continuous images by using Helmholtz equation, and has been proved to be effective when it is used in image processing. However, few investigations are focused on its application to the visualization of turbulent flow and PIV analysis.

The purpose of this paper is first applied the smart visualized information processing to turbulent flow images and PIV image for improving its temporal resolution and generating animation images. Then the generated images with the higher temporal resolution are used to visualize turbulent structure and obtain PIV results.

SMART VISUALIZED INFORMATION PROCESSING

Any image with arbitrary resolution can be generated by solving the following image governing (Helmholtz) equation:

$$\nabla^2 \mathbf{V} + \varepsilon \frac{\partial}{\partial t} \mathbf{V} = -\rho \tag{1}$$

where $\mathbf{V}$, ε and σ are the image scalar potential to be evaluated, medium parameter and image source density, respectively.

In order to generate the image with any resolution from Eq.(1), a finite difference method is used. The discrete form of Helmholtz equation can be written as:

$$C\mathbf{V}_t + D\frac{d}{dt}\mathbf{V}_t = \mathbf{F} \tag{2}$$

Further, Equation (2) may be rewritten in the standard form.

$$\frac{d}{dt}\mathbf{V} = -C^{-1}D\mathbf{V} + C^{-1}\mathbf{F} \quad or \quad \frac{d}{dt}\mathbf{V} = -A\mathbf{V} + \mathbf{F}' \tag{3}$$

Let $\mathbf{X}_1, \mathbf{X}_2, .., \mathbf{X}_n$ respectively be the *n*-th order characteristic vectors of the characteristic values λ_1, λ_2, . . , λ_n in the matrix A, then we have

$$Z = \begin{bmatrix} \mathbf{X}_1 & \mathbf{X}_2 & . & \mathbf{X}_n \end{bmatrix} \tag{4}$$

Z is called the modal matrix. It is well known that any solution vector **V** of a physical system may be obtained as linear combinations of the characteristic vector *Z*:

$$\mathbf{V} = Z\mathbf{Y} \tag{5}$$

According to the linear transformation, Equation (3) can be transformed into the following form.

$$\frac{d}{dt}\mathbf{Y} = -(Z^T A Z)\mathbf{Y} + Z^T\mathbf{F} \tag{6a}$$

or

$$\frac{d}{dt}\mathbf{Y} = -\Lambda_{Physical}\mathbf{Y} + Z^T\mathbf{F} \tag{6b}$$

where $Z^T AZ = \Lambda_{physical}$. The formal solution of modal Eq.(6) is given by

$$\begin{aligned} \mathbf{Y} &= \Lambda_{Physical}^{-1} Z^T \mathbf{F} + e^{-\Lambda_{Physical} t}\left(\mathbf{Y}_0 - \Lambda_{Physical}^{-1} Z^T \mathbf{F}\right) \\ &= \mathbf{Y}_{Final} + e^{-\Lambda_{Physical} t}\left(\mathbf{Y}_{Start} - \mathbf{Y}_{Final}\right) \end{aligned} \tag{7}$$

If U_t represents an image between the images U_{Start} and U_{Final} in image system, Equation (7) can be expressed as

$$\mathbf{U}_t = \mathbf{U}_{Final} + e^{-\Lambda t}\left[\mathbf{U}_{Start} - \mathbf{U}_{Final}\right] \tag{8}$$

where If $\Lambda = \Lambda_{physical}$, the state transition matrix *A* of physical system can be represented in terms of the modal matrix *Z*:

$$A = Z\Lambda Z^T \tag{9}$$

where

$$\Lambda = \begin{bmatrix} \lambda_1 & 0 & . & 0 \\ 0 & \lambda_2 & . & 0 \\ . & . & . & . \\ 0 & 0 & . & \lambda_n \end{bmatrix} \tag{10}$$

Therefore any image U_{i+1} between the images U_i and U_{i+2} can be generated by using

$$\mathbf{U}_{i+1} = \mathbf{U}_{i+2} + \varepsilon^{-\Lambda\Delta t}\left[\mathbf{U}_i - \mathbf{U}_{i+2}\right] \tag{11}$$

The image state transition matrix Λ is obtained by:

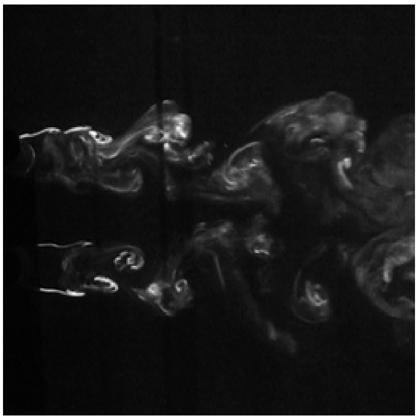
$$\Lambda = -\frac{1}{\Delta t}\ln\left[\frac{\mathbf{U}_{i+1} - \mathbf{U}_{i+2}}{\mathbf{U}_i - \mathbf{U}_{i+2}}\right] \tag{12}$$

APPLICATION TO TURBULENT WAKE IMAGES

The experiment was carried out in a water tunnel with a square working section (0.15m x 0.15m) of 0.5 m long. Two side-by-side acrylic circular cylinders with an identical diameter of 10 mm were horizontally mounted. A wake flow was generated at a Reynolds number of 750. A thin laser sheet, which was generated by Argon Ion laser source, provided illumination vertically, and the images were recorded with a digital video camera with a frame rate of 24 frames/s.

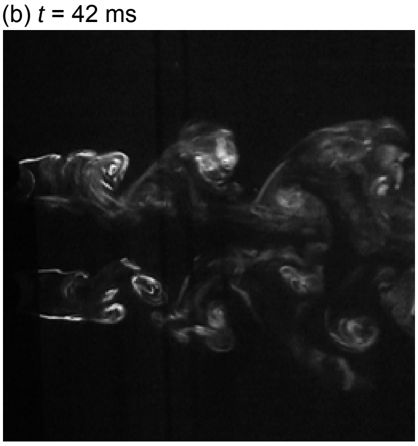
Figure 1 shows three successive original images of wake flow. The flow pattern immediately behind the cylinders is symmetrical about the flow centerline. Two consecutive rolling-up vortices of opposite sign appear on each side of the wake. In order to improve the temporal resolution of the image and to analyze the wake flow structure, the wake images are analyzed by the smart visualized information processing. First, the image state transition matrix Λ is determined based on the three successive images of Fig.1 by using Eq. (12). Then the solution (8) of image Helmholtz equation (1) can generate any image between the starting (Fig.1 (a)) and final (Fig.1(c)) images. The images generated between the first image (Fig.1a) and the second one (Fig.1b) are shown in Fig.2. These successive images exhibit the flow pattern and the development of vortical structures can be instantaneously observed. As shown in Fig.2, the formation and growth of rolling-up vortices at different instants, marked by arrows, can be clearly visualized, which cannot be found in original images.

From the above results, one is can say that the smart visualized image processing technique is effective in flow visualization. Further investigation will focus on multi-resolution analysis of vortical structures.



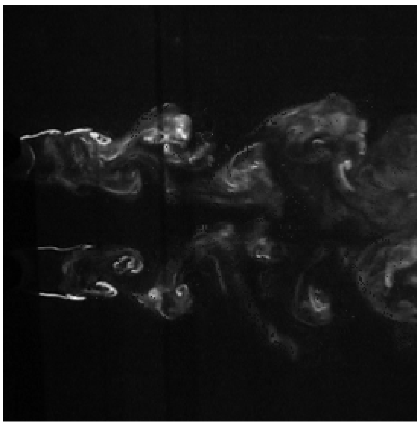
(a) t = 0 ms

(b) t = 42 ms

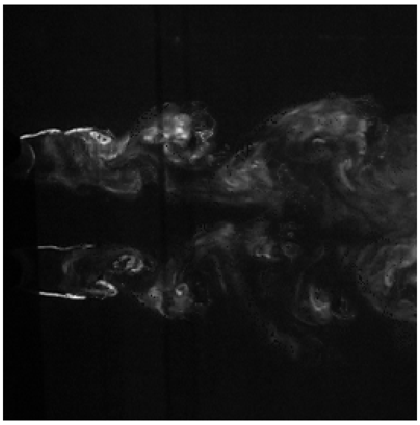


(c) t = 84 ms

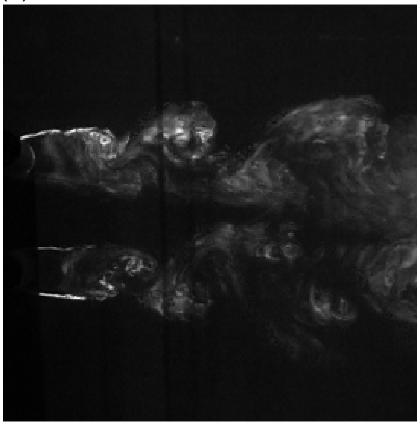
Fig.1. Original wake flow images.



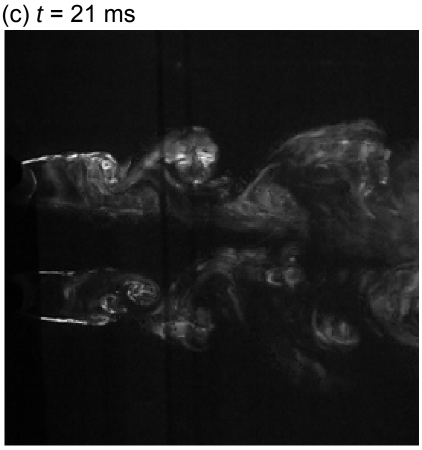
(a) t = 4.2 ms



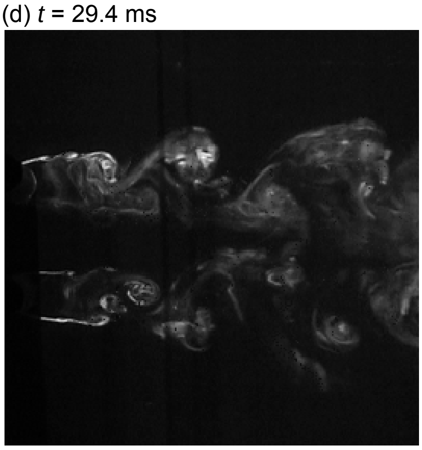
(b) t = 12.6 ms



(c) t = 21 ms



(d) t = 29.4 ms



(e) t = 37.8 ms

Fig.2. Generated wake images.

APPLICATION TO PIV

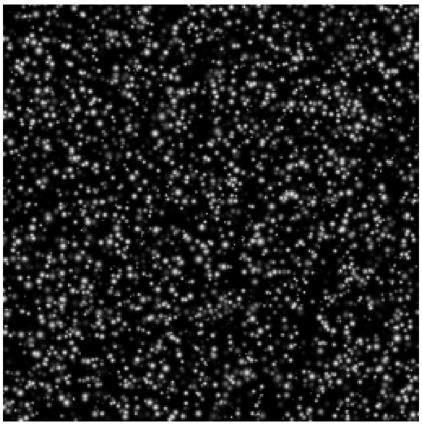
Particle Image Velocimetry (PIV) is a non-intrusive flow visualization technique and is now firmly established as a powerful fluid dynamics tool to measure flow velocity in the area of fluid mechanics. Even more important than this remarkably improved performance of the PIV technique, is its unique ability to capture instantaneous full-field flow and thus to allow the detection of spatial structures in unsteady flows quantitatively, which is not possible with other experimental techniques. Although a cross-correlation CCD array camera can record pairs of images with a frequency of 10 Hz, it is important to develop software to improve the temporal resolution. Comprehensive reviews on the principles, the historical development and application of PIV were given by Adrian (1991) [2], and the details will not be repeated here.

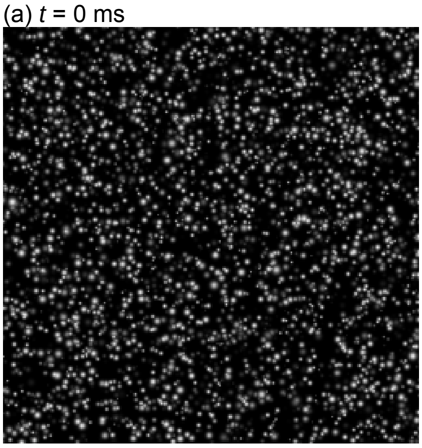
For typical method of PIV, instantaneous planar velocity vector is usually determined by cross-correlating the interrogation windows (or small image masks) in two successive PIV images separated by a known time interval. In typical approaches, the image data from a window taken in the first image and that from a window at the same position in the second image are cross-correlated. The discrete cross correlation coefficient is defined as

$$R(m,n)=\frac{\sum_i\sum_j f(i,j)g(i+m,j+n)}{\sum_i\sum_j f^2(i,j)\sum_i\sum_j g^2(i,j)} \tag{13}$$

where $f(i,j)$ and $g(i,j)$ represent the pixel intensities of the interrogation windows at pixel locations (i,j) in the first and second images, respectively. The function $R(m,n)$ measures the correlation of the discrete functions $f(i,j)$ and $g(i,j)$ when they are relatively shifted by (m,n) pixels. The location of the maximum cross-correlation peak gives the mean displacement of the particles in the interrogation window within a known time interval. The instantaneous velocity vector at location (i,j) is calculated from this mean displacement.

In order to evaluate the smart visualized information processing, the standard PIV images of a steady two-dimensional wall shear flow, which were developed by the Visualization Society of Japan, are used in this study. Figure 3 shows three successive PIV standard images (256x256 pixels with an 8bit grayscale) with the time interval $\Delta t = 0.033s$. The number of particles is 4000. The average particle diameter and standard deviation are 5 and 1.4 pixels, respectively. The average image velocity is 7.4 pixels/interval and the maximum image velocity is 15 pixels/interval. The average and maximum out-of-plane velocities are respectively 0.017 and 0.10 intervals^{-1}. Figure 4 shows the accurate velocity field by analyzing two successive standard PIV images (Fig.3 (a) and (b)) using PIV technique.


(a) t = 0 ms


(a) t = 33 ms

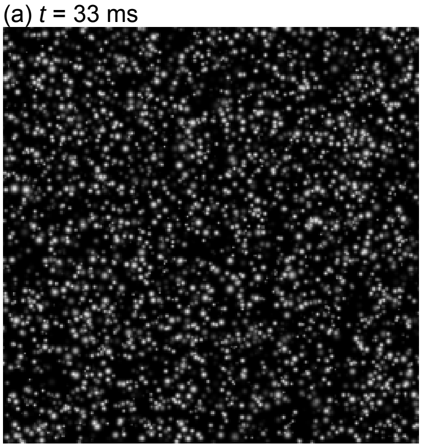

(a) t = 66 ms

Fig.3. Original standard PIV images

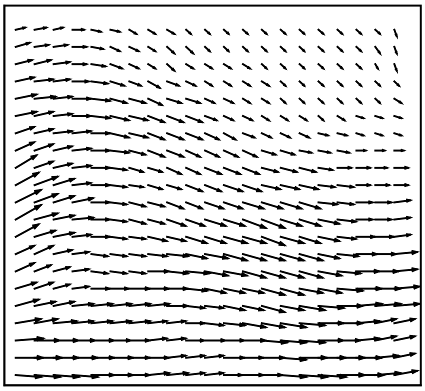
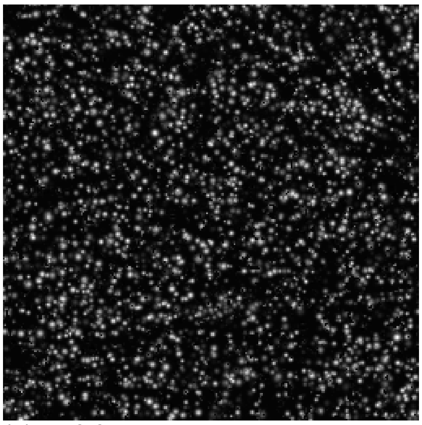
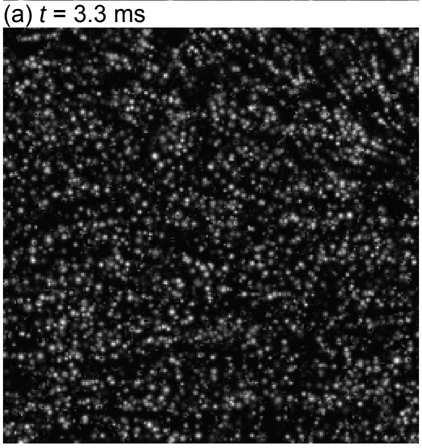
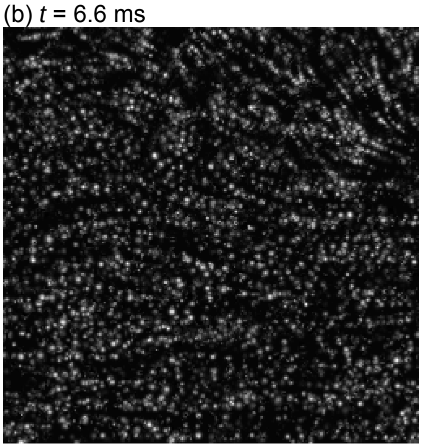
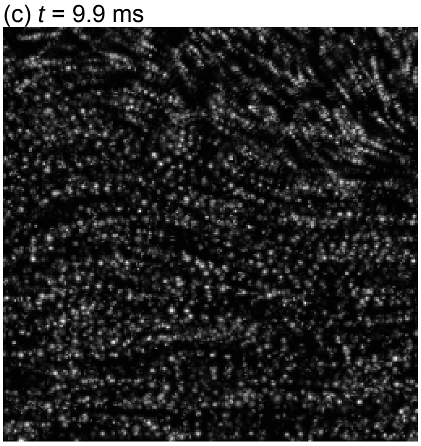


Fig.4 Accurate velocity field of PIV standard images

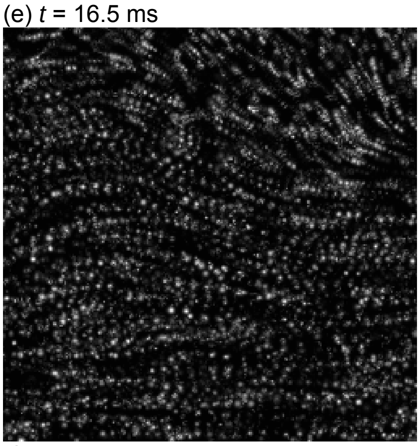

(a) t = 3.3 ms


(b) t = 6.6 ms

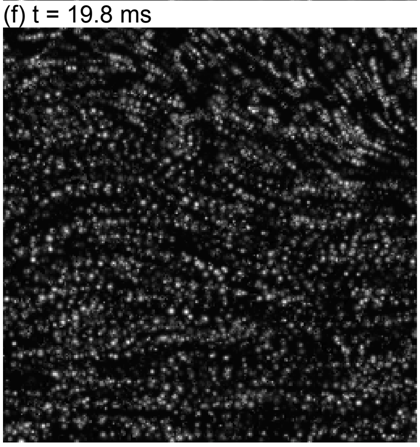

(c) t = 9.9 ms


(d) t = 13.2 ms

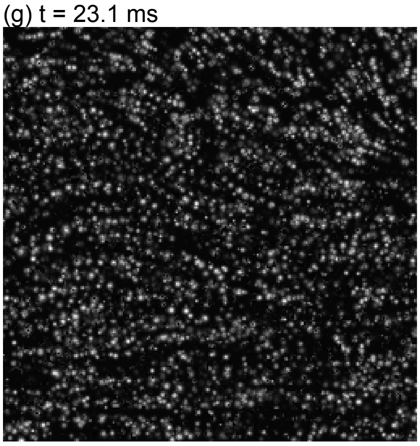
(e) t = 16.5 ms



(f) t = 19.8 ms



(g) t = 23.1 ms



(h) t = 26.4 ms

Fig.5. Generated standard PIV images

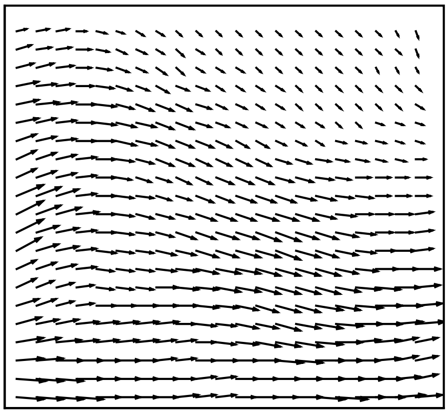


Fig.6. Reconstructed velocity field based on generated PIV standard images

In this study three successive PIV standard images (Fig.3) are analyzed by the smart visualized image processing. Figure 5 shows the generated PIV images between the first and second PIV standard images. These successive images exhibit clearly the particle flow patterns or streamlines, which cannot be found in original images of Fig.3. The velocity vector field that is obtained from the generated two images of Fig.5 (b) and (h) using cross-correlation PIV method (Eq.13) is shown in Fig.6. It is evident that the PIV result of generated images agrees with the accurate solution in Fig.5. This result verifies that the smart visualized image processing technique can generate the higher temporal resolution of PIV images and is effective in PIV system.

CONCLUSIONS

Although preliminary, this paper demonstrates that the smart visualized image processing is very effective when applied to the flow image processing and PIV technique for generating the higher temporal resolution of images. Further investigation will focus on the detail analysis of turbulent structures and evaluating measurements of instantaneous velocity and turbulent statistics in the complex turbulent flows.

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