Tomo-PIV measurement of flow around an arbitrarily moving body with surface reconstruction

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Abstract A three-dimensional (3D) surface shape of an arbitrarily moving body in flow field was reconstructed using the DAISY descriptor and the epipolar geometry constraints. The measurement of a moving surface was simultaneously conducted with tomographic PIV flow measurement. The moving body was placed within the flow field so that the moving body interacts with the fluid flow. Experimental images were captured using the tomographic PIV system which consists of four high-speed cameras and high-power green LEDs. The originally captured images, which contain the shape of the arbitrarily moving body and tracer particles, were separated into the particle and surface images using the Gaussian smoothing. The weak contrast of the surface images was improved using the localized histogram equalization. Finally, the histogram equalized surface images and the separated particle images were used to measure the surface shape and the 3D flow velocity, respectively. The proposed method was applied to the flag flapping and cylinder rotating cases.

1. Introduction

The flow-structure interaction (FSI) phenomena are frequently observed in nature. The biomimetics, especially, is an emerging field in FSI field because many animals have an optimum mechanism in the mobility. For example, the swimming fish and the flying bird are very significant and interesting mechanisms. The two mechanisms reduce the drag force from fluid by deforming their bodies and make propulsion by flapping their wings and tails. These are the reasons why many researchers have focused on the FSI phenomena.

This study proposes an experimental method for investigating the FSI system. The experimental approaches have an important advantage that the active deformation of fish or bird can be investigated without any prescribed motions. The present technique is suitable for observing the natural events without biased information due to the prediction of moving motions, and also includes PIV flow measurement with the interacting surface measurement. Experimental measurement is a practical approach to investigate the FSI problem. There are several studies that measure flow field and an arbitrarily moving body simultaneously. Jeon and Sung (2010) developed two-dimensional (2D) analyzing algorithms by convolving the texton to track the interface of the moving body. They also developed three-dimensional (3D) technique for simultaneous measurement (Jeon and Sung, 2012). Adhikari and Longmire (2012) proposed the visual hull method using silhouette masks of the moving object for reconstructing its shape.

In this study, we propose an image processing technique for simultaneous measurement of flow and an arbitrarily moving body. A 3D surface shape of a moving body was reconstructed by matching the DAISY descriptors, and the flow velocity was measured by tomographic PIV method. This technique was applied to the flows around a flapping flag and a rotating cylinder.

2. Experimental method

Figure 1 shows an experimental apparatus of the volumetric flow measurement system. High-power green LED module (PT-120-G-C11-MPF, Luminus Devices) was used to illuminate the whole test section. Combination of plano-convex lens with cylindrical lens was used to illuminate the test volume from uncollimated light from the flat type LED. The LED driving circuit was made on a bread board according to the way of Buchmann et al. (2012). The thickness of the test volume was 20 mm and the width and height were 80 mm and 70 mm, respectively. Images of the LED illuminated test volume were captured by 4 high-speed cameras (PCO. 1200hs). Each camera was calibrated by placing a calibration object into a water tank. Control points were marked on the surface of the calibration object at non-coplanar position. The direct linear transformation (DLT) method was applied to calculate the perspective transformation matrix of each camera. The 3D real coordinate and 2D image coordinate pairs of detected control points were used to calculate the perspective transform matrix for each camera. Fluorescence particles and long pass filters were used to adjust the brightness of light intensity from tracer particles and moving body surface. A flexible flag, attached to a rigid rod, and a rotating cylinder were selected as an arbitrarily moving object inside flow field. For a robust measurement of surface shape, natural patterns were used than artificially marked fiducial dots.

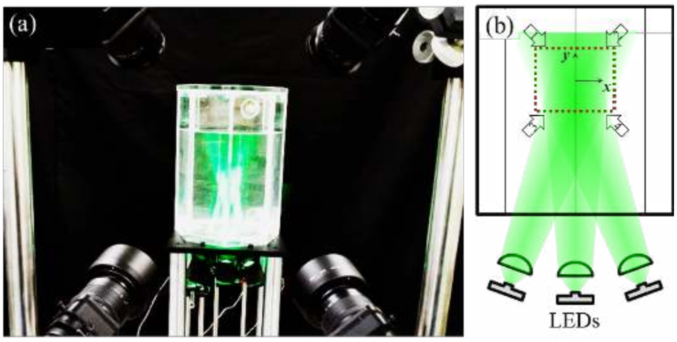

Fig. 1 Experimental setup

3. Image processing

In the case of fluid-structure interaction (FSI), a region of interest of flow field is adjoined with the boundary of a moving body. According to Jeon and Sung (2012), 3D PIV images for the FSI have overlapping scenes of particles and surface. The overlapped original image cannot be directly used in PIV calculation nor the surface shape reconstruction. PIV calculation can be disrupted by bright background level of the surface pattern, and the surface reconstruction can also be limited by the overlapped particles. For this reason, the original image should be separated into the particle image and the surface image. Figure 2a is an originally captured image for tomographic PIV flow measurement when a flag is flapping in the fluid. The image separation was performed using the Gaussian kernel smoothing because their typical size are significantly different. From the image separation process, particle and surface images were produced as in Fig. 2b and c, respectively. The separated particle image (Fig. 2b) is now able to be used for the tomographic PIV flow measurement because its background level is dark enough. The separated surface image (Fig. 2c) was converted to the histogram equalized surface image (Fig. 2d) before used for the surface shape reconstruction.

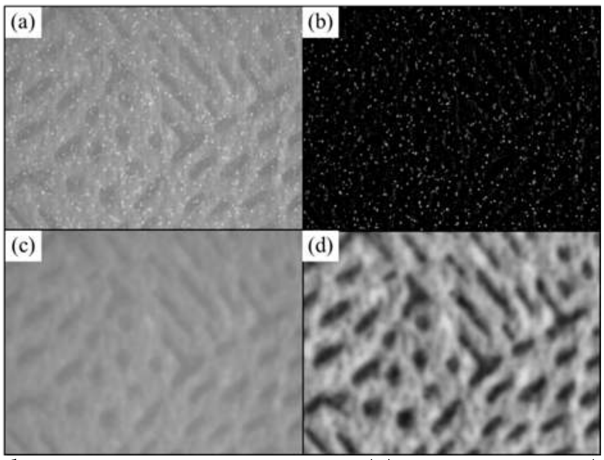

Fig. 2 Image separation and histogram equalization result (a) original image, (b) separated particle image, (c) separated surface image, and (d) histogram equalized surface image

4. Surface reconstruction

A dense 3D surface reconstruction was performed by using the DAISY descriptors (Tola et al. 2008, 2010) from the surface images and the epipolar geometry. The matching strategy of the DAISY descriptor was adopted from Tola et al. (2012) and modified in the present study to apply for four-camera combination. As shown in Fig. 3, one camera (e.g. camera 1) was selected as a reference camera and the other three cameras (e.g. camera 2 to 4) were regarded as additional cameras for a stereo vision. The DAISY descriptor matching was performed for each pixel (u, v) using the reference camera image to achieve a dense reconstruction. The pixel position $(u, v)_i$ in the reference camera image has the corresponding epipolar lines l_j in other camera images. The descriptor $D(u_i, v_i, c_i)$ of the reference camera image was compared with the descriptor $D(u_j, v_j, c_j)$ in the other camera images where the $(u, v)_j$ is placed on the epipolar line l_j. The three-dimensional coordinates (x, y, z) can be calculated from $(u, v)_j$ which has the most similar descriptor with $(u, v)_i$. The consistency of the descriptor matching was performed by comparing z values from j=2, 3, 4. This matching procedure was repeatedly conducted by changing the reference camera to the other cameras. The matched descriptor pairs were triangulated to the 3D coordinates as surface points where these 3D points contain both inlier and outlier points (Fig. 4a). The outlier points among the triangulated points were filtered out by calculating the k-th minimum distance from other points.

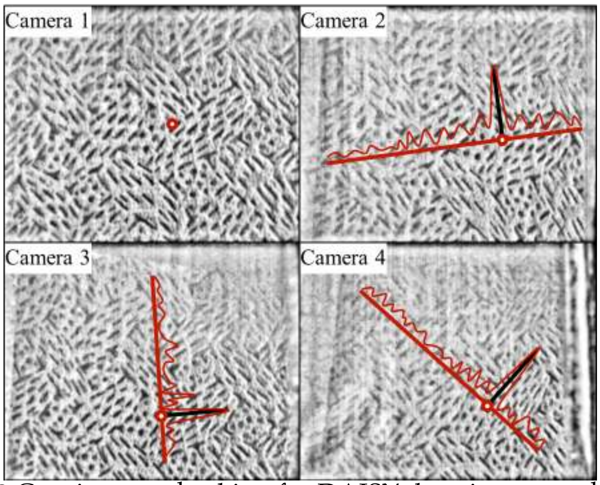

Fig. 3 Consistency checking for DAISY descriptor matching

As the surface reconstruction was performed in a dense manner, the inlier points has numerous short distances with other points while the outlier points have only a few short distances. The k value for the k-th minimum distance as 20 and twice of averaged distance value was selected as a criterion. The filtered inlier points (Fig. 4b) were converted as a surface mesh data through the Delaunay triangulation (fig. 4c). Finally the surface shape was reconstructed with the converted mesh data.

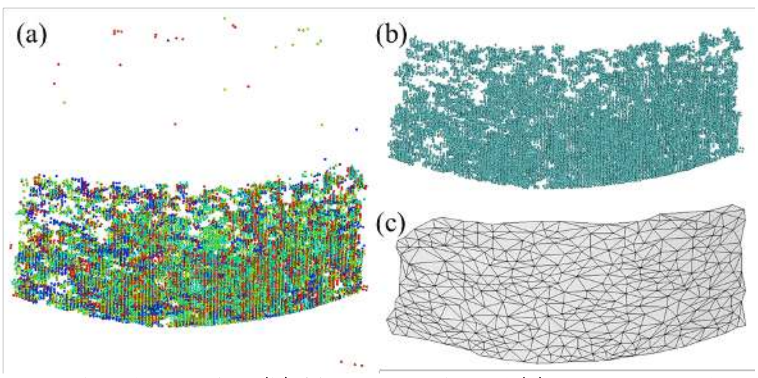

Fig. 4 (a) Triangulated particles, (b) filtered result and (c) reconstructed surface mesh

5. PIV measurement results

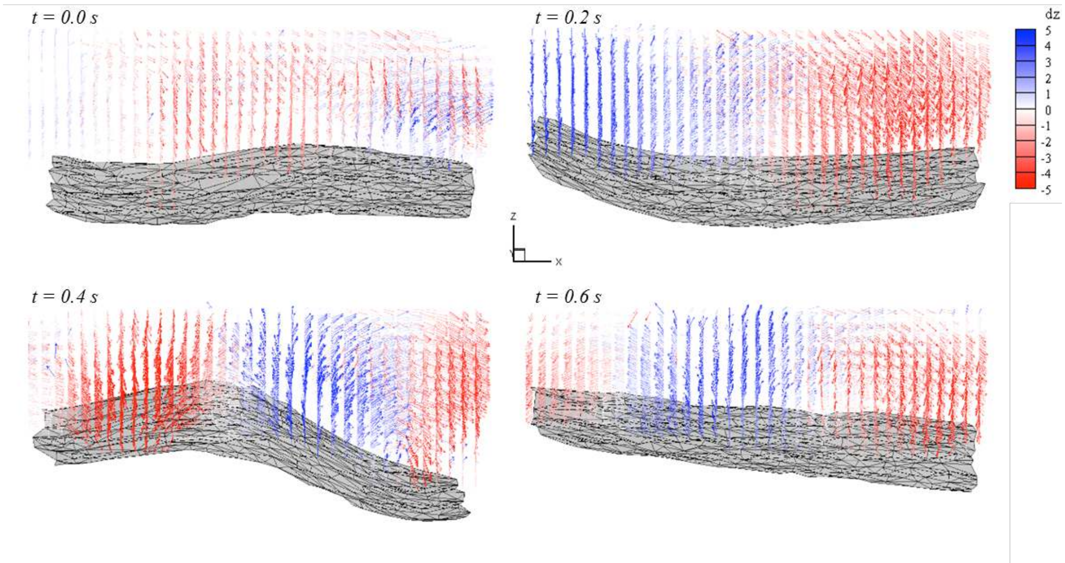

Fig. 5 Surface reconstruction and flow measurement around a flapping flag

Flow around an arbitrarily moving body was successfully measured with the surface reconstruction. The flow and the surface were simultaneously measured by a single PIV experiment. 3D-3C velocity field data was calculated by the tomographic reconstruction and 3D direct non-zero voxel cross-correlation while the surface shape was reconstructed using the DAISY descriptor. Figure 5 shows time series of the simultaneous measurement of flapping flag motion and fluid flow. The velocity vectors in Fig. 5 were colored by z-directional velocity of the flow. The $+z$ and $-z$ directional velocities are represented as blue and red, respectively. From the result, the change of flag surface shape and the flow field are consistent throughout the experiment. Figure 6 shows the flow field around a rotating cylinder. The contour surface body in Fig. 6 represents the onsection of the rotating cylinder surface. The rotating axis of the cylinder was on the y axis and the flow was driven by the rotating surface. The high speed streak is represented by the iso-surface in this figure.

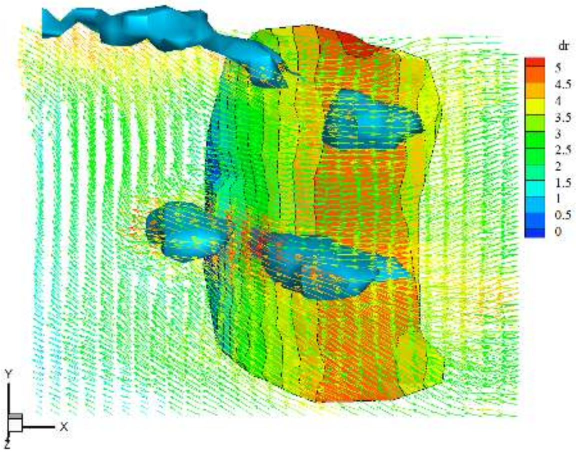

Fig. 6 Surface reconstruction and flow measurement around a rotating cylinder

6. Conclusions

Full 3D flow field and the 3D surface shape of an arbitrarily moving body were measured by tomographic PIV and the DAISY descriptor. Fluorescence particles and a long pass glass filter were used to simultaneous imaging. Captured images were separated to the particle and surface images by Gaussian smoothing. Separated surface images were converted by the localized histogram equalization. The histogram equalized surface images were used to reconstruct the surface shape of the moving body, and the separated particle images were used to measure the flow field. The flow field was calculated by tomographic PIV algorithm with the reconstructed surface information. The proposed method was applied to flow measurement around a flapping flag and a rotating cylinder. The measured velocity field and the surface shape showed a good consistency, and this method will be a practical method for fluid structure interaction.

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