ABSTRACT

A single-camera PIV system based on combination of color-coded illumination and color high-speed video camera has been developed. The system realizes 3D3C velocity measurement in a volume, but does not require particle imaging in multiple directions. The working principle is categorized into smoke-imaging PIV since smoke particles are much smaller than single pixel in image plane, and particle number density is much larger than the case of color PTV. Thus, the principle is totally different from PTV assisted with color coding. Instead, the accuracy severely depends on how the integral equation of color-signal overlapping is reversely solved in smoke-present space, i.e. removal of color contamination. The contamination occurs with hardware characteristics of illumination device, light-scattering property of smoke particles, and also with optical receiving property of a camera used. We propose an inverse matrix equation to remove the contamination, and show the feasibility numerically and experimentally through several model flow tests assuming its application to wind tunnel experiments.

1. INTRODUCTION

Turbulent flows that always have three-dimensional nature demand advanced and innovative measurement systems in order to fully resolve the flow physics. For example, elementary structures of turbulence can be captured only by 3-D 3-C (three-dimensional, three-component) velocimetry because of complex networks organized by distorted vortex tubes. 3-D measurement technique for airflows is still in the stage of development. Recent tomographic Particle Image Velocimetry (PIV) system has enabled 3-D 3-C velocimetry [1]. But it requires three or more cameras with fine adjustments, and is limited in measurements of relatively small volumes. This costly instrument also cannot be applicable for flows in complex fluid machinery and for flows in large atmospheric space. These disadvantages are sticking points to introduce the technique as open 3-D measurement methods.

We propose a novel technique for imaging these flows, which allows us to determine the 3-D 3-C velocity vector fields at a given frame rate just using a single camera view. The camera captures a full color intensity distribution of tracers that are illuminated by color coded volumetric projection of light. If tracer particles are large enough and do not overlap with others on the image, depth positions of the particles can be determined by the color information of particles. Such “color PTV” has been developed well and is applied to various flow systems (e.g., Ido et al. [2], McGregor et al. [3]). Using micron order particles, however, are required to keep sufficient traceability in general airflow measurements. For example, water mist is used for airflow visualizations. This is a primary cause which makes a difficulty on the reconstruction of particle distributions. Color scattering light from each layer are overlapped because a pixel of image sensor captures multiple particles. It makes impossible to determine individual 3-D position of the tracer particles. For such “color PIV”, Murai et al. [4] have reported that the 3-D tracer concentration can be obtained by the principle of computed tomography, which employs backward projection of color components in the direction perpendicular to the image plane. They have examined accuracy of the reconstruction by numerical simulation, however, the accuracy has never evaluated quantitatively in actual measurements of airflows.

For the establishment of the 3-D 3-C velocimetry using misty tracer, a simple 3-D measurement system, which employs color striped light constructed with three layers as an illumination, is focused on as an early stage of our study. Each layer has different primary color, Red, Green and Blue. Color information in the image corresponds to the integration of color information at each layer, and thus reconstruction process utilizes the principle of computed tomography. The overlapped color components of a visualized image, Red, Green and Blue, do not represent the layers that are illuminated by each color. Color components perceived by color imaging devices depend on optical property of particles and spectral response characteristic of the charge device [5]. The influence of the dependence on particle color identifications has never been examined quantitatively in the previous study. In this research, the effects depending on the characteristics are evaluated quantitatively. Reconstruction of 2-D tracer density distributions in each layer from the color components with considering the effects is achieved by a simple process. On the obtained tracer distribution, 3-L 2-C (three-layer, two-component) velocity vector field is calculated with general planar PIV. Applicability of this method is evaluated in a measurement of airflow passing a delta wing. Vortical stricter generated by the delta wing, a
strong, longitudinal vortex pair, were already studied well [6], and is suitable for the evaluation. In addition, we demonstrate 3-D 3-C measurement using three layered color illumination with an interval between the layers. 3-D 3-C velocity vector field are measured with 3-D cross correlation analysis applied for spatio-temporal voxel interrogation.

2. MULTIPLE LAYER PLANAR PIV

2.1 Experimental setup

Fig.1 shows the schematic diagram of experimental setup. The equipment consists of a water mist generator, a LCDP (Liquid Crystal Display Projector) and a HSV (High-Speed Video camera). The cord length and the aspect ratio of the delta wing are \( c = 100 \) mm and \( A = 2.0 \). The delta wing model is set at an angle of attack, \( \alpha = 20 \) degrees. Velocity of main stream is controlled at \( U_0 = 1.5 \) m/s. Wake behind the delta wing is visualized with water mist and color illumination generated by LCDP (EIKI inc., LC-XT3D). The illumination is constructed with three layers perpendicular to the direction of main stream. Each layer is separated by three primary colors in order of Blue, Green and Red from trailing edge as shown in Fig. 2. Depth of a layer is \( \lambda = 100 \) mm as same scale as the chord length \( c \). Visualized flow is captured by color HSV (Photron inc., FASTCAM-MAX) which can registers 24-bit RGB. Frame rate, shutter speed and image size are set 125 fps, 1/125 s and 1024\(^2\) pixel in imaging.

\( x-y-z \) coordinate system is defined as horizontal, vertical and main stream axes. The origin of coordinate system is put in the center of trailing edge. In this paper, we define non-dimensional coordinate scale divided by chord length \( c \) as \( x/c, y/c, z/c \). Reynolds number defined by velocity of main stream \( U_0 \) and chord length \( c \) is \( Re = 10500 \). In this method, depth of measurement volume is 300 mm, which cause difference of spatial resolution in each layer. Therefore, we adopt \( z/c = 0.5, 1.5 \) and 2.5 as representative positions in Blue, Green and Red layer and define spatial resolutions in each layer. The resolutions are 0.39 mm/pixel, 0.36 mm/pixel and 0.33 mm/pixel.

![Figure 1. Schematic diagram of experimental setup](image1)

![Figure 2. Color illumination in wake of a delta wing model](image2)

2.2 Removal of color contamination

Misty tracer distribution is reconstructed from visualized image including overlap of colors. To evaluate the sensitivity of imaging sensor in the camera against incident Red, Green, Blue color information, response of color image sensor to scattering light with single color layer was analyzed. Positions and depths of each layer are fixed with the case of multi-color layer illumination. Here, \((R, G, B)\) are defined as color components sensed by image sensor. \((R_l, G_l, B_l)\) are defined as color intensities of scattering lights produced by tracer particles in each layer. When only Red layer is illuminated, the image is scattered by tracer particles in the Red layer. \(R\) component is mainly responded by image sensor, but \(G\) and \(B\) components are also somewhat sensed. The effect is caused by color filter of the image sensor principally. To elucidate characteristics of the response, the relationship between \(R\) and other two components, \(G\) and \(B\), is analyzed in all pixels of 1024 images taken by the HSV on the condition. Assuming that \(R = R_l\), incidences of \(G\) and \(B\) in relation to \(R_l\) are calculated. This image processing is also conducted to Green and Blue single color illuminations.
**Figure 3.** \((R, G, B)\) response characteristics of a image sensor to Red, Green and Blue scattering intensity.

Fig. 3 shows the characteristics of the image sensor on this experimental condition. Horizontal axis and vertical axis mean intensity of scattering light and responses of two color components without the illumination colors. Value of incidence is shown color scale. These seem linearly increase with increasing intensity of illumination color. The linear characteristics are described by

\[
\begin{bmatrix}
    R \\
    G \\
    B
\end{bmatrix}_{\text{Red}} =
\begin{bmatrix}
    1 \\
    a_1 \\
    a_2
\end{bmatrix}
\begin{bmatrix}
    R_L \\
    b_1 \\
    b_2
\end{bmatrix},
\]

(1)

\[
\begin{bmatrix}
    R \\
    G \\
    B
\end{bmatrix}_{\text{Green}} =
\begin{bmatrix}
    1 \\
    a_3 \\
    a_4
\end{bmatrix}
\begin{bmatrix}
    G_L \\
    b_3 \\
    b_4
\end{bmatrix},
\]

(2)

\[
\begin{bmatrix}
    R \\
    G \\
    B
\end{bmatrix}_{\text{Blue}} =
\begin{bmatrix}
    1 \\
    a_5 \\
    a_6
\end{bmatrix}
\begin{bmatrix}
    B_L \\
    b_5 \\
    b_6
\end{bmatrix},
\]

(3)

where \(a_1\) to \(a_6\) and \(b_1\) to \(b_6\) are parameters calculated by the color information analysis. Response of the Red illumination as shown in Fig. 3 (a) is applied eq. (1), where \(a_1\) and \(b_1\) mean slope and intercept of the \(G\)-response. The \(B\)-response is reflected by \(a_2\) and \(b_2\). Similarly, responses of the Green illumination and Blue illumination shown in Fig.
3 (a) and (b) are elucidated by eq. (2) and eq. (3). These parameters are determined by least-square method from results of the color response analysis as shown in Table 1.

<p>| | | | | |</p>
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| $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ | $a_6$  
| 0.183 | 0.0936 | 0.511 | 0.256 | 0.103 | 0.285  
| $b_1$ | $b_2$ | $b_3$ | $b_4$ | $b_5$ | $b_6$  
| -2.01 | -2.20 | -2.64 | -3.66 | -0.629 | -1.28  

By assuming that color components sensed by image sensor are constituted by linear sum of scattering lights produced in each layer, following algorithm is proposed for reconstruction of tracer distribution. Namely, color components of visualized image ($R, G, B$) are constructed by linear sum of eq. (1) to eq. (3). ($R, G, B$) are described by

$$
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix} = 
\begin{bmatrix}
1 & a_3 & a_5 \\
a_1 & 1 & a_6 \\
a_2 & a_4 & 1
\end{bmatrix} 
\begin{bmatrix}
R_L \\
G_L \\
B_L
\end{bmatrix} + 
\begin{bmatrix}
b_3 + b_5 \\
b_1 + b_6 \\
b_2 + b_4
\end{bmatrix}.
$$

Intensity distributions in each layer ($R_L, G_L, B_L$) represent tracer density distribution. ($R_L, G_L, B_L$) are calculated by inverse operation of eq. (4) instantaneously. This algorithm finally enables reconstruction of 2-D 3-L tracer distributions. Images acquired in the visualization are processed and reconstructed three distributions in each layer as shown in Fig. 4. This reconstruction filters out smoke density caused by scattering lights from other layers. For example, Green scattering light influences especially $R$ component (Fig. 3 (b)), therefore the Red layer in Fig. 4 (a) may contain artifacts. Indeed, the reconstruction with the calibration successfully eliminates the artifact in an area indicated by white circle in Fig. 4 (a).

2.3 Velocity vector field in wake of a delta wing model

Fig. 5 shows velocity vector distributions obtained by general planar PIV based on gray level difference accumulation. The number of processing images is 1024 frames. The vector fields represent time averaged 2-C velocity fields at $x$-$y$ cross section for 1024 time steps. The magnitude of vector is normalized by $U_0$ and is shown by color scale. In Blue layer, just behind the delta wing model ($0 < z/c < 1.0$), a primary vortex pair is observed clearly above $y/c = 0$. The vortex pair locates around $y/c = 0$ in Green layer ($1.0 < z/c < 2.0$). Result in Red layer ($2.0 < z/c < 3.0$), however, vortex...
structures are not captured clearly because of low sensitivity of the image sensor for Red and instability of the vortex pair at this position. The measurement with the method shows that different wake structures are captured in each layer and the structures are similar to widely known flow passed delta wing.

![Figure 5. Velocity vector field in Blue, Green and Red layer time-averaged between 1024 frames](image)

3. SPATIO-TEMPORAL 3-D CORRELATION PIV

In this chapter the method of 3-D velocity vector measurement for split color illuminated images is explained. Fig.6 shows the optical configuration that utilizes three principal colors with interval $\lambda$ for measuring spatial development of wake structure.
Fig. 6 shows pre-processing and conversions of original images. Firstly the image is downsized from $1024^2$ to $512^2$ pixel to unify the fluctuation wavelengths in space and time. Cubic matrix-based median filtering is then applied in order to reduce optical noise and turbulent eddy-originated brightness fluctuation. The image conversion (d) depicts the image in which co-existing brightness component among three colors is subtracted so that any pixel consists of two color components. This process realizes de-whitening effect which helps sensitive color correlation than for the original. The color variance image (e) shows the image of temporal color fluctuation standardized upon gray image. The time gradient image (f) is computed from temporal gradient of color components.

The 3-D velocity vector components are measured with 3-D cross correlation analysis applied for spatio-temporal voxel interrogation as defined by

$$
C = \frac{\sum_i \sum_j \sum_k \alpha_i \beta_j \gamma_k}{\left( \sum_i \sum_j \sum_k \alpha_i^2 \beta_j^2 \right)^{\frac{1}{2}}} \left( \sum_i \sum_j \sum_k \beta_j \gamma_k \right) \left( \sum_i \sum_j \sum_k \alpha_i \gamma_k \right)
$$

(5)
where $\alpha$ and $\beta$ are the pair of different color distributions which are the function of space $(i,j)$ and time $(k)$ in digital voxel space. The spatio-temporal brightness advection vector $(\Delta i, \Delta j, \Delta k)$ is determined when the cross correlation $C$ takes the highest value within a searching box. The velocity components are obtained by

$$
\begin{bmatrix}
U \\
V \\
W
\end{bmatrix}
(x, y, z^*, t) =
\begin{bmatrix}
M \cdot \Delta i / (\Delta t \cdot \Delta k) \\
M \cdot \Delta j / (\Delta t \cdot \Delta k) \\
\lambda / (\Delta t \cdot \Delta k)
\end{bmatrix}
$$

(6)

where $M$ stands for the magnification factor, and $z^*$ indicates the z-coordinate of the central location between two layers for which correlation analysis is implemented.

Fig. 8 shows one of the velocity vector distributions we obtained with the present system. The vectors in blue color mean downward flow induced by the Delta wing, which fluctuates in time as we see in the figure (b). Before obtaining this result, we examined so many combinations of image conversion and 3-D correlation analysis with different interrogation options. The best type of the image conversion has been found to be color variance image. As shown in Fig. 9, this image conversion amplifies the temporal color fluctuation and provides an adequate wavelength in 3-D brightness distribution, which is comparable between space and time for a given interrogation box.

![Figure 8](image1.png)

(a) $x$-$y$ section  
(b) $y$-$t$ section

**Figure 8.** Velocity vector distribution obtained by 3-D correlation analysis implemented between blue and red layers (i.e. the velocity distribution at $z/c=1.50$)

![Figure 9](image2.png)

(a) $x$-$y$ section  
(b) $x$-$t$ section  
(c) $y$-$t$ section

**Figure 9.** Spatio-temporal 3-D color variance images

4. CONCLUSIONS

A new method of PIV for measuring 3-D velocity vector distribution in airflow has been developed. The method consists of color-coded illumination for smoke distribution, removal of color contamination, and 3-D PIV conducted in spatio-temporal three-dimensional domain. In this paper we focused on the removal of color contamination which occurs due to RGB characteristics in instrumental signal propagations. An inverse matrix solver allows us to remove the color contamination, and to formulate the method of smoke density distribution in spatio-temporal domain. The inverse matrix is mathematically obtained from a forward matrix that describes the RGB modification from illumination to receiving. The forward matrix is obtained by a series of color-response calibration which takes only a few seconds prior
to measurement. Once the matrix is acquired, we can compute each instantaneous 3-D smoke density distribution with
the inverse matrix operation, and can measure 3D3C velocity field using spatio-temporal 3D voxel-base cross
correlation PIV algorithm the same as ordinary tomographic PIV. The most important merit of the present method is
freedom from restriction of measurable volume, for instance, a flow in tennis court size can be measured using powerful
color illuminator. The system is suitable for measurement of flows that dominate in one direction like in a wind tunnel
flow because main stream can be converted to rapid change of colors while secondary flow perpendicular to the main
stream is precisely measured as ordinary in-plane velocity.

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