Color Flow-Visualization Photography and Digital Image Processing Techniques*

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Color flow-visualization photography and digital image processing techniques have been developed for the purpose of flow measurement in the flow field of a circular vessel with recirculation flow. The path-lines of aluminum powder were photographed on a color reversal film by illuminating it in red, white, and green in turn within an exposure time. The pixel values in red, green, and blue for 256 steps prepared by the drum-scanner as the digital image data of the film, the resultant stimulus and the trichromatic coordinates of each pixel were evaluated from them. The pixels for path-lines were distinguished from the background by the threshold-level of resultant stimulus, and their colors were determined by using the principal component obtained from combined and standardized residuals for the regression formulas of trichromatic coordinates. The velocity vectors can be derived from both the location and color of pixels, and the time interval of white color illumination.

Key Words: Flow Measurement, Flow-Visualization, Color Image Processing, Trichromatic Coordinates, Principal Component Analysis, Residual, Velocity Vectors

1. Introduction

Numerous methods for flow velocity measurements in a flow-visualization picture have been developed, in which the information of flow is extracted with the aid of a computing system. As for the method using a single picture by the tracer method, there have been several works; for example: the methods of manual operation[8]; and utilizing the picture obtained in its initial position by instantaneous flash[10]; and for the plural pictures: the methods of employing the three pictures photographed by short-exposure and long-exposure by two cameras[3]; the matching technique of each path-line among successive pictures[4]; and the mutual correlation of two digital image[9]. In these methods, the determinations of initial and terminal points on the path-line are difficult to establish by the use of only one picture, and the errors owing to the locations or image data between pictures may be considerable by the method of plural pictures.

This paper describes the developments of color flow visualization photography[6] and image processing techniques capable of determining the flow direction of tracer by the difference of path-line color and obtaining velocity vectors.

2. Color Photography and Image Processing

2.1 Experimental apparatus and photography

In the measurement of flow velocity using the visualization picture by the tracer method for complicated flow fields such as those having recirculating flow, one requirement is to determine the flow direction of the tracer. In this stage, it is determined by the difference of color of the path-line photographed on a color reversal film with the three color illuminations changed in turn within an exposure time. The flow field used is one in a circular vessel with recirculation flow induced by issuing water from a feed pipe on the vessel axies, which resembles the separation pattern that occurs inside a combustion chamber[7]. The conditions of flow visualization and photography are sum-

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marized in Table 1, where \( D_w \) is the inside diameter of the feed pipe, and \( U_w \) is the average velocity in it.

A schematic illustration of the experimental apparatus is shown in Fig. 1.

The flow-visualization picture was taken by a camera placed in front of a reservoir illuminated in the vessel by a light passed through a slit attached to a lighting box. After the carriage in the box was traversed by the drive of a pulse motor, the camera receiving the signal from the photo-interrupter, the shutter of the camera was opened, and the color of illumination turned at time \( T_1 \) and \( T_2 \) with the passing of color cellophane mounted on the carriage in front of the slit. The measurements of time \( T_1 \) and \( T_2 \), and the control of the motor were carried out by a micro computer.

2.2 Image processing

Image processing was performed by the use of ACOS-6 and sub-system, RSIPS-6/DT. The information contained in the visualization film were obtained as pixel values in red (R), green (G) and blue (B) for 256 steps by the transmission drum-scanner attached to the sub-system. From the pixel values, which represent information concerning brightness and color, the resultant stimulus \( S \) and trichromatic coordinates denoted by \( c \) with subscripts \( i = 1, 2 \) and 3 indicating the red, green and blue respectively of each pixel are represented as follows:

\[
F = R + G + B = c_1 \cdot r + c_2 \cdot g + c_3 \cdot b
\]

where,

\[
R = R \cdot r, \quad G = G \cdot g, \quad B = B \cdot b
\]

\[
S = R + G + B
\]

\[
c_1 = R/S, \quad c_2 = G/S, \quad c_3 = B/S
\]

\[
c_1 + c_2 + c_3 = 1
\]

\( F \) is color stimulus, while \( R, G \) and \( B \) are stimulus values of red, green and blue, and \( r, g \) and \( b \) reference stimuli respectively.

3. Velocity Measurement

3.1 Visualization picture and pixel values

The colors of illumination used were selected from the results of photographing the tracers in still water with illumination by the use of red, green and blue cellophane, and by the non use of cellophane respectively, as red, white and green, since the tracers photographed with the illumination of red, white and green were more visible in the pictures. The color cellophanes of red and green were set on the carriage at intervals. Figure 2 shows an example of the picture photographed under the conditions of an exposure time of 0.904s and a white illumination time of 0.543s. The path-lines being photographed with each illumination color, an accurate measurement of them might be possible with a manual operation, though the colors are indistinguishable in Fig. 2 for the picture printed in monochrome. The film of this picture was scanned.
with a pixel width of 0.05 mm, and image processing was performed in the region denoted by $P$ in Fig. 2. Total pixel counts in this region are $300 \times 400$, and a practical pixel length based on the radius of the circular vessel (14.0 cm) is 0.0376 cm. The histograms of pixel values are shown in Fig. 3 with a logarithm scaled ordinate. They have sharp peaks because the influence of the illumination for the large number of pixels of the background is so small that the pixel values are at the same level. The pixels with pixel values near to those at maximal frequency are of the background, and the pixel values of path-line pixels, which are greater than those at maximal frequency exist in a comparatively small range of pixel values.

3.2 Distinction between path-line and background

The pixels for path-lines were distinguished from

the background by the threshold of $S$. The histogram of $S$ is shown in Fig. 4 with the logarithm scaled ordinate, where the threshold of $S = 413$ was evaluated above $S$ at the maximum frequency as the level corresponding to the first point at which the second order derivative of the frequency with the class width of $S$ for 3 changes in sign. The separated pixels of path-lines are shown in Fig. 5, where $r$ and $z$ are coordinates of the radius and axial with the origin in the center of the bottom wall of the circular vessel, and the number of pixels for path-line, $N$ is 6721, and of path-lines supposed the conglomerate of pixels connected to at least one of neighbouring 4 pixels is 270.

3.3 Detection of pixel color

The pixel color of path-line is detected next. The pixel color is expressed in $c_i$, which is a function of the value $S$. The relations between $S_a$ and $c_a$, are shown in Fig. 6, where subscript $a$ ($a = 1, 2, \ldots, N$) indicates the number of pixel of the path-lines, and $\bar{c}_i$ are
regression formulas of \( c_{ni} \) as,
\[
\tilde{e}_i = a_{1i} + a_{2i} S + a_{3i} S^2 + a_{4i} S^3 \quad (i = 1, 2, 3)
\] (6)
and the regression coefficients, \( a_{1i}, a_{2i}, a_{3i} \) and \( a_{4i} \), satisfy
\[
\sum_{i=1}^{3} a_{1i} = 1, \quad \sum_{i=1}^{3} a_{2i} = 0, \quad \sum_{i=1}^{3} a_{3i} = 0, \quad \sum_{i=1}^{3} a_{4i} = 0 \quad (7)
\]
and residuals \( e_{ai} \) are given by
\[
e_{ai} = c_{ni} - \tilde{e}_i \quad (a = 1, 2, \ldots, N; i = 1, 2, 3) \quad (8)
\]

As \( S \) is increased, \( c_i (i = 1, 2, 3) \) approaches to trichromatic coordinates of white, \( c_i = 0.333 \). This fact is ascribed to the interference susceptibility of the \( c_{ni} \) with \( S \) near to threshold from the trichromatic coordinates of the background. And, it is postulated that the pixel with \( \tilde{e}_i \) (\( i = 1, 2, 3 \)) at each \( S \) is white, and that the pixel color is detected by the use of \( e_{ai} \) (\( i = 1, 2, 3 \)) which indicates the degree of departure from white.

The relations of \( e_{ai} \) and \( \sum_{i=1}^{3} e_{ai} \) to \( S \) are shown in Fig. 7. \( e_{ai} \) satisfies approximately
\[
\sum_{i=1}^{3} e_{ai} = 0 \quad (a = 1, 2, \ldots, N) \quad (9)
\]

Figure 8 shows the relations of deviation \( \delta_{ai} \) to \( S \), where
\[
\delta_{ai} = \sum_{i=1}^{3} c_{bi}/N - c_{ai} \quad (N = 0; i = 1, 2, 3) \quad (10)
\]

\( N_i \) is the total number of pixels at each \( S \), and subscript \( \beta (\beta = 1, 2, \ldots, N_2) \) indicates the number of pixel. From the comparison of Fig. 7 with Fig. 8, it is observed that the shapes of distributions of \( e_{ai} \) and \( \delta_{ai} \) to \( S \) differ from each other in the range of \( S > 650 \) where \( \delta_{ai} \neq 0 \). This fact is due to the bad approximation of \( \tilde{e}_i \) as can be seen from Fig. 6, and the difference of \( c_{ai} \) in the pixel with \( c_{ai} > 650 \) is so small that the color seemed to be white, and hence the difference of color appears in the very limited ranges of \( S \). In the region of \( S \) near to threshold, the width of the distribution of \( e_i \) (\( i = 1, 2, 3 \)) at each \( S \) is narrow despite the great number of \( N_i \). This is thought to be caused by the influence of the trichromatic coordinates of the background on \( c_i (i = 1, 2, 3) \) in those ranges.

The scatter diagrams among \( e_{ai} (i = 1, 2, 3) \) which satisfy Eq. (9) are shown in Fig. 9, and the variances, covariances and correlation coefficients of \( e_i \) (\( i = 1, 2, 3 \)) are listed on the diagonal line, above it, and below it in Table 2, respectively. \( e_{ai} \) and \( e_{ak} \) are great respectively in the red and green pixels. The correlation coefficient between \( e_1 \) and \( e_2 \) is negative and large, but that between \( e_1 \) and \( e_3 \) small. In spite of the small correlation coefficient between \( e_1 \) and \( e_2 \), the correlation between \( e_1 \) and \( e_3 \) is great in the region of large \( e_1 \) and comparatively great in the region of large \( e_2 \). For these reasons, though the characteristics of pixel color seem to be represented by \( e_{ax} \) and \( e_{ax} \), those of green have difficulty appearing owing to the small variance compared with red. Therefore, \( e_{ax} \) and \( e_{ax} (= e_{ax} - e_{ax}) \)
freshly prepared are used. Further, since the widths of distributions of \( \varepsilon_i \) \((i=2, 4)\) vary with \( S \), after the pixels with \( S_a > 650 \) are removed as white, \( \varepsilon_{si} \) \((i=2, 4)\) for the pixels with \( 413 < S_a < 650 \) are standardized by
\[
\varepsilon_i = b_i + b_i S + b_i S^2 + b_i S^3 \quad (i=2, 4) \tag{11}
\]
which are approximated formulas of the standard deviations of residuals at each \( S \), \( \sigma_{si} \)
\[
\sigma_{si} = \sqrt{\frac{\sum (\varepsilon_{si})^2}{(N_a-1)}} \quad (N_a \geq 2 \; ; \; i=2, 4) \tag{12}
\]

Table 2 Variances, covariances and correlation coefficients of residuals

<table>
<thead>
<tr>
<th>( \varepsilon_1 )</th>
<th>( \varepsilon_2 )</th>
<th>( \varepsilon_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon_1 )</td>
<td>( 1.80 \times 10^{-4} )</td>
<td>( -3.02 \times 10^{-5} )</td>
</tr>
<tr>
<td>( \varepsilon_2 )</td>
<td>( -0.335 )</td>
<td>( 4.51 \times 10^{-5} )</td>
</tr>
<tr>
<td>( \varepsilon_3 )</td>
<td>( -0.870 )</td>
<td>( -0.173 )</td>
</tr>
</tbody>
</table>

obtained by the least square method as the weight of \( N_a \).

The relations of \( \sigma_{si} \) and \( \varepsilon_i \) \((i=2, 4)\) to \( S \), and of standardized residuals, \( \varepsilon_{si}' = \varepsilon_{si}/\varepsilon_i \) \((i=2, 4)\) to \( S_a \) are shown in Fig. 10 and Fig. 11 respectively. The variances of \( \varepsilon_{si} \) in each \( S \) become uniform compared with

![Fig. 10 Relation of standard deviation to resultant stimulus](image)

![Fig. 11 Plot of standarized residuals vs. resultant stimulus](image)

![Fig. 12 Scatter diagram of standarized residuals](image)
those in Fig. 7. The scatter diagram between $\varepsilon_{x}$ and $\varepsilon_{z}$ is shown in Fig. 12. $\varepsilon_{x}$ reveal the characteristics of color fairly compared with those in Fig. 9.

As the results above indicate, since the detection of pixel color seems possible using the $\varepsilon_{i}$ ($i=2, 4$), they are correlated by principal component analysis. The variances, covariance and correlation coefficient of $\varepsilon_{i}$ ($i=2, 4$) are shown on the diagonal line, above it and below it in Table 3 respectively. With these values, the principal component $Z$ of each pixel is obtained by

$$Z_{a} = 0.711 \varepsilon_{2} - 0.704 \varepsilon_{4}$$  (13)

### Table 3: Variances, covariance and correlation coefficient of standardized residuals

<table>
<thead>
<tr>
<th></th>
<th>$\varepsilon_{2}$</th>
<th>$\varepsilon_{4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{2}$</td>
<td>1.010</td>
<td>-0.581</td>
</tr>
<tr>
<td>$\varepsilon_{4}$</td>
<td>-0.581</td>
<td>0.995</td>
</tr>
</tbody>
</table>

The histogram of $Z'$, which is integer part of $Z_{a}$, is shown in Fig. 13. $Z'$ is large in red, and small in green pixels.

The pixel color is decided using the threshold of $Z'$, $Z_{b}$ and $Z_{c}$ according to the magnitude of $Z_{a}$ as the pixel with $Z_{a} > Z_{b}$, $Z_{a} \leq Z_{b} \leq Z_{c}$; and $Z_{a} > Z_{c}$ is red, white and green respectively. However, in the decision of the color using threshold $Z_{b}=14$ and $Z_{c}=-34$ obtained automatically by discriminant analysis, red pixels appear to be white for too large a number of red pixels. This fact may depend on the equivocal appearance of three dimensional features of the color in the histogram of $Z'$. For this reason, the thresholds of $Z'$ were obtained as $Z_{b}=27$, $Z_{c}=30$ which were levels for which the ratios of the area of red, white and green on the film, 12.4%, 82.0% and 5.6%, which was magnified 100-fold by the projection, were consistent with the ratios of the number of pixels of red, white and green for 27 path-lines selected randomly from Fig. 5.

### 3.4 Velocity vectors

Velocity vector $U$ is obtained using the conglomerates of colored pixels connected to at least one of 4 directions of neighbouring pixels within one path-line by the procedure shown in Fig. 14. Figure 14(a) shows the pixels of a path-line distinguished from the background, and Fig. 14(b) displays the pixel conglomerates of red, white and green in a path-line in which green and white pixels in contact with white and red pixels are surrounded by marks ○ and □ respectively. The velocity vector is obtained using the coordinates of the center of gravity of the pixels surrounded by marks ○ and □, and the time of white illumination, $\Delta T = T_{1} - T_{1}$. Their coordinates, $G_{r}(r_{i}, z_{i})$ and $G_{t}(r_{i}, z_{i})$, are

$$G_{i}(r_{i}, z_{i}) = \left( \sum_{i=1}^{N} \frac{r_{i}}{M_{i}}, \sum_{i=1}^{N} \frac{z_{i}}{M_{i}} \right).$$

![Fig. 13](image1.png)

**Fig. 13** The histogram of principal component of $Z'$

![Fig. 14](image2.png)

**Fig. 14** Process of velocity vector determination


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Fig. 15 Velocity vectors obtained from path-lines in Fig. 5

\[ G(r_r, z_r) = \left( \frac{N_1}{Z_{1o}} r_{x1}/M_1, \frac{N_1}{Z_{2o}} z_{x1}/M_1 \right) \]  \hspace{1cm} (14)

where \( k_1 \) and \( k_2 \) are pixels surrounded by marks \( \Box \) and \( \bigcirc \), \( G_1(r_{x1}, z_{x1}) \) and \( G_2(r_{x2}, z_{x2}) \) are their coordinates, and \( M_1 \) and \( M_2 \) are the number of their pixels, respectively. Figure 14(c) shows the velocity vectors obtained using \( u \) and \( v \), the \( U \) component of the \( r \) and \( z \) directions respectively, and the coordinates of displacement, \( P_0(r_0, z_0) \), where

\[ u = (r_t - r_t)/\Delta T, \hspace{1cm} v = (z_t - z_t)/\Delta T \]  \hspace{1cm} (15)

\[ P_0(r_0, z_0) = ((r_t + r_t)/2, (z_t + z_t)/2) \]  \hspace{1cm} (16)

Here, a path-line lacking either red or green pixels in contact with white pixels is removed as the undeterriable path-line of initial or terminal points. Furthermore, correct combination is sought for having more than two of either conglomerates, which is regarded as an overlapping path-line. It was sought by methods such as: (1) the combination by which deviation for the distance between initial and terminal points is minimized, and (2) the number of maximum and minimum points for distribution of curvature along the outline pixels of path-line. However, the correct combination may not be sought on occasions by (1); and to obtain the curvature is difficult for a large width of pixels compared with the tracer size by (2). At this stage, from the sum of the average of value of \( S \) for the pixels on the straight line joining the initial and terminal points, after the combination which takes the maximal sum is selected, the crossed path-lines are removed.

Figure 15 shows the velocity vectors obtained from the path-lines in Fig. 5, where above the recirculation flow near the bottom and along the side wall of the vessel, a small recirculation with reverse flow is observed, the occurrence of which is attributed to the sudden enlargement of the path of influent water above the recirculation. The total number of velocity vectors in Fig. 15 is 92, and of removed vectors from 37 vectors which are obtained from 16 overlapping path-lines is 14. And the number of the path-lines with neither red nor green pixels in contact with white pixels is 67, and those without either red or green are 36 and 70 respectively.

The summation of C.P.U time required in this kind of image processing, from the input of image data to the output of velocity vectors, is about 100 s, excepting the time needed to plot the figures.

3.5 Measurement errors

The accuracy of this method is influenced by the accuracy of both: (A) the information contained in the visualization picture, and (B) the method to extract the information from the picture. The following factors exert an influence on (A): (1) the traceability of the tracer; (2) the number of tracers and their distribution in the flow field; (3) velocity evolution during the white illumination time; (4) the refractive effect of the water, the distortion of the film, and the mounting method of the camera; (5) the thickness of the lighting plane; (6) the chromatic aberration by the lens etc. Most of the errors owing to the above mentioned factors were estimated fully in reference (1), and the errors in this method are estimated in the same way.

The following factors affect (B): (7) the resolutions of pixel value and location by the drum-scanner; (8) the method for the measurement of white illumination time; (9) the methods for the determination of the path-line and pixel color, and of the distance in image processing.

As the purpose of this paper is the development of color flow visualization photography and image processing techniques, the accuracy of measurement affected by the above mentioned factors will be investigated in the near future. However, concerning 20 velocity vectors selected randomly from Fig. 15, the maximal difference between the length of the straight line joining the centers of both edges of the white part on the film measured in the same way used to obtain the threshold of \( Z^* \), and the length obtained by image processing is 0.184 cm, and the average difference is 0.0496 cm. The maximal difference of angle between the line measured and the line obtained by the processing is 31.6 degrees, and the average difference is 6.84 degrees. The error of time measurement is less than 50 ms, as the width of slit is 0.3 cm, the moving speed of color cellophane is 12.9 cm/s, and time is measured by 0.1 ms unit.
3.6 The characteristics of this method

The measurement accuracy in this method is markedly affected by the width of a pixel and the thresholds in the image processing, and by time measurement; however, the accuracy of the image processing will be able to be improved by the use of small width pixels or high property illumination, and that of time measurement by a higher speed carriage traverse etc. Therefore, it is thought that more accurate measurements can be expected with the device development of information processing; and the disadvantage of the conventional method is supplemented to a certain extent by the use of this method. Thus, the following advantages for this method should be described: (1) the measurement is free from errors due to the locations and image data between pictures because of the use of one picture; (2) the flow direction of the tracer is found even in a complicated flow field; (3) the flow field is little affected by the tracer because of the use of aluminum powder as a tracer; (4) wide range velocity measurements may be possible by the appropriate selection of the time measurement unit, the pixel width and the scale of the picture.

4. Conclusions

The development of color flow visualization photography and image processing techniques capable of measuring flow velocity were attempted. The results obtained are as follows.

(1) Color flow visualization photography capable of determining the initial and terminal points of a path-line has been developed.

(2) Pixels of the path-line were distinguished from the image picture by the threshold of the resultant stimulus.

(3) The color of path-line pixels was detected by the thresholds of the principal component obtained from combined and standarded residuals for the regression formulas of trichromatic coordinates.

(4) Image processing techniques capable of obtaining a velocity vector have been developed in the flow field with recirculation.

References


