Development of 3-D Stereo PIV and Its Application to a Delta Wing

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Key Words: : homogeneous coordinate system, 3-D stereo PIV, camera modeling, delta wing, LEX(Leading Edge Extension), spiral vortex

Abstract

A process of 3-D stereo particle image velocimetry(PIV)was developed for the measurement of an illuminated sliced section field of 3-D complex flows. The present method includes modeling of camera by a calibrator based on the homogeneous coordinate system, transformation of the oblique-angled image to the right-angled image, identification of 2-D velocity vectors by 2-D cross-correlation equation, stereo matching of 2-D velocity vectors of two cameras, accurate calculation of 3-D velocity vectors by homogeneous coordinate system, removal of error vectors by a statistical method followed by a continuity equation criteria, and finally 3-D display as the post processing. An experimental system was also used for the application of the proposed method. Two high speed digital CCD cameras and an Argon-Ion Laser for the illumination were adopted to clarify the time-dependent characteristics of the leading edge extension(LEX) in a highly swept shape applied to a delta wing found in modern air-fighters.

1. Introduction

PIV(Particle Image Velocimetry)[1] gives us several advantages compared with other velocity measurement techniques. Until the present time, many related research works have been done with remarkable successes by various PIV system throughout the world. Among them, 3-D PIV is well recognized as a powerful means for the quantitative measu-rement of 3-D complex flows frequently encounter-ed in the flow analysis. It also affords researchers useful flow information in engineering sense as well as real-time velocity components[2][3]. Three-Dimensional PIV is usually classified into two methods, 3-D volume PIV and 3-D stereo PIV. 3-D volume PIV[4][5] can give us three velocity components simultaneously in principle for any 3-D complex flows but it is not matured in practical point and it needs more developing time in the future as the decisive measurement solution. On the other hand, 3-D stereo PIV[6] is widely used as a standard 3-D measurement solver in PIV world and it has shown many successful examples in academic research and industry application by virtue of its sliced 3-D measurement volume approach. In the present study, An 3-D angular method[7] free from the camera orientation limitation was adopted for three CCD cameras. The homogenous coordinate system suggested in this work can obtain the particle positions projected on image coordinate, not by camera coordinate. By this homogeneous system, the process of camera distortion correction and calculation of the orientation parameters[9][10] are not necessary with additional decrease of calculation

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errors. And it also reduces the processing time by direct use of the image coordinates. For an applica -tion example, LEX attached delta wing found in modern air-fighters was chosen. Three-dimension al flow behavior of the large scale vortex pair and vortex collapse phenomenon were particularly noticed from the time-dependent observation.

2. Stereo PIV

2.1 Algorithm procedure

The image grabber and two or more cameras first acquire images. Subsequent camera modeling work is continued from the image coordinates and ground coordinate via the camera calibration model. Obtained original images are generallydistorted by the arbitrary camera setting angle and position. Transformation of the original image into real size of rectangular form is followed. Identification of particles are done by the conventional 2-D cross-correlation algorithm by using the two consecuti-ve flow images from two cameras. And then stereo matching is needed by applying the two dimensional velocity vectors from each camera. Final 3-D velocity vectors are obtained by the 3-D coordinate equation. As the post-processing, elimina-tion of the error vectors is carried out by the auto-matic and manual method and 3-D distance reverse interpolation is applied for any vector coordinate based display.

2.2 Camera modeling

The camera model for the projected particles in the 3-D coordinate system can be identified by the transformation matrix by the camera geometric para-meters.

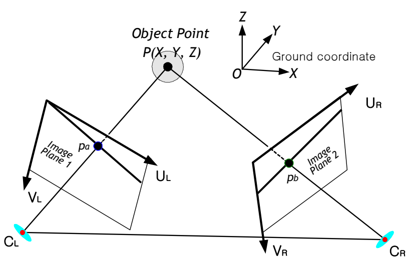


Fig. 1 Homogeneous coordinate system

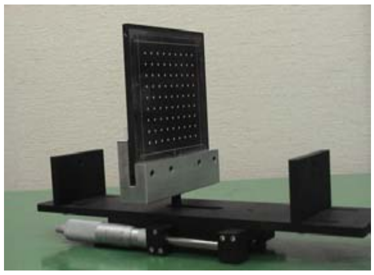


Fig. 2 Camera calibrator

The camera model for the projected particlesin the 3-D coordinate system can be identified by the transformation matrix by the camera geometric parameters. The process of the image projection is composed of the several parameters such as camera translation, rotation, scaling and perspective trans-formation and so on. In the present study, the transformation matrix is obtained by the ground coordinate from the camera calibration model and image coordinate. The relation of the ground coordinate(X, Y, Z) and image coordinate(u, v, t) is shown as eq.(1), This equation means the trans-formation of the ground coordinate into image coordinate via rotation, translation and perspective transformation matrix.

$$(X,Y,Z,1)=\begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 \\ C_{21} & C_{22} & C_{23} & 0 \\ C_{31} & C_{32} & C_{33} & 0 \\ C_{41} & C_{42} & C_{43} & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 & C_{14} \\ 0 & 1 & 0 & C_{24} \\ 0 & 0 & 0 & C_{34} \\ 0 & 0 & 0 & C_{44} \end{bmatrix}=(u,v,0,t) \tag{1}$$

Here, (X,Y,Z) indicates the ground coordinate and the first matrix multiplied by the ground coordinate means the camera translation and rotation, the second is perspective transformation matrix based on the perspective plane Z=0, and (u, v, t) is the homogeneous coordinate of the image plane. Equation(2) show the relation of the image coordi-nate from the camera(U, V) and the homogeneous coordinate. The simplification of eq.(1) produces the matrix Rij of 4x3 which transforms the three-dimensional object into the two-dimensional image

$$U = u/t$$
$$V = v/t \tag{2}$$

as eq.(3), This 4 x 3 Rij matrix is thematrix of the camera modeling, one of the essential processes in the present algorithm.

$$\left(X,Y,Z,1\right)=\begin{bmatrix}R_{11} & R_{12} & R_{13}\\ R_{21} & R_{22} & R_{23}\\ R_{31} & R_{32} & R_{33}\\ R_{41} & R_{42} & R_{43}\end{bmatrix}=(u,v,t) \tag{3}$$

Equation(3) is changed into eq.(4)

$$\begin{aligned} u &= XR_{11} + YR_{21} + ZR_{31} + R_{41} \\ v &= XR_{12} + YR_{22} + ZR_{32} + R_{42} \\ t &= XR_{13} + YR_{23} + ZR_{33} + R_{43} \end{aligned} \tag{4}$$

The combination of eq.(4) and the equation, u-U×t =0, v-V×t=0 eliminates the u, v, t and the homogeneous coordinate is transformed by the image plane coordinate from camera as eq.(5).

$$\begin{aligned} &XR_{11}+YR_{21}+ZR_{31}+R_{41}-U(XR_{13}+YR_{23}+ZR_{33}+R_{43})=0 \\ &XR_{12}+YR_{22}+ZR_{32}+R_{42}-V(XR_{13}+YR_{23}+ZR_{33}+R_{43})=0 \end{aligned} \tag{5}$$

Figure1 shows the homogeneous coordinate and if image coordinate pa, pb and object ground coordinate P(X, Y, Z) is known, the elements of the twelve camera modeling matrix(from R11 to R43)can be obtained from eq.(5). Twelve equations are necessary to solve the twelve unknown elements but R43can be replaced by an arbitrary number 1 because eq.(5) is obtained from the homogeneous matrix. For eleven unknowns, eleven equations are solved by the least square method. Figure2 shows the camera calibration model with 0.01 mm spatial resolution in the camera depth direction. This model consists of one thin metal plate of its size 100 mm(H)×100mm(V) and circle marks of 0.3 mm diameter, arrayed by 9(H)×9(V), 10 mm interval. Byrevolving traversing knob to obtain 1mm advance at one time and nine times in the depth direction, ground coordinates for the perspective transformation equation are obtained. Therefore, the number of reference mark is 729(9H×9V×9D). The 3-D coordinates of the reference marks and 2-D coordinates projected on image plane are used to solve the perspective transformation equation, yielding the eleven matrix elements.

2.3 Correction of image distortion

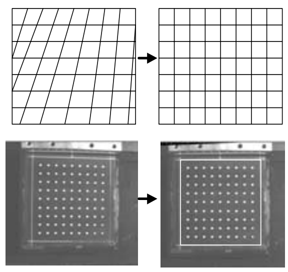
As shown in Fig.3, acquired images are different from the real images owing to the arbitrary camera angle and position. To correct this distorted image, the perspective transformation equation (6) is used to obtain the distortion correction parameters between the image coordinates and the ground coordinates of the measured section.

$$X=\frac{b_1x+b_2y+b_3}{b_4x+b_5y+1}\ ,\qquad Y=\frac{b_6x+b_7y+b_8}{b_4x+b_5y+1} \tag{6}$$

Here, b1, b2, b3, b4, b5, b6, b7, b8 are transformation parameters and they are obtained by the least square method. x, y are image coordinates and X, Yare ground coordinates of the measured section. At least, more than four ground and image coordinates are used to get the transformation parameters. If N image coordinates of (x, y) and corresponding ground coordinates(X, Y) are known, observation equation (7) is obtained from eq.(6). And then, by solving the eq.(7) by the least square method, transformation parameters are obtainable.

$$TB = Z \tag{7}$$

In Fig.3, (a) is a distorted original image and (b) is the corrected image by the perspective transformation equation (7).



(a) oblique angled image (b) transformed image

Fig. 3 Image transformation

2.4 Stereo matching and calculation of 3-D coordinates

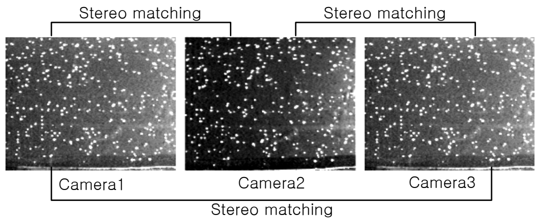


Fig. 4 Stereo matching of 3 CCD cameras

If the matrix of the camera modeling for the two images from the cameras and 3-D projected coordinates are known, the acquisition of the 3-D spatial position information is possible. The principle of the stereo matching of the 3-D stereo PIV[11][12][13]is based upon two ideas, The first one is to obtain the 2-D velocity vectors by applying the cross correlation algorithm to the two frame images. The second one is to get the 3-D velocity vectors by using the 3-D coordinate formula which adopts the homogeneous coordinate system as eq.(8)

$$[F]\times[X]=[D] \quad (8)$$

In principle, two cameras only are sufficient for the 3-D stereo PIV but in this study, three cameras are available to enhance the measurement accuracy.
Fig. 4 shows the example of the stereo matching when three cameras are used.

3. Experimentation

3.1 Experimental model

For applying the present 3-D stereo PIV algorithm, a PIV measurement system as in Fig.5 was adopted[14][15]. Fig.5 shows the specification of the delta wing model with LEX. In case of LEX-off wing, the chord length is 150mm and the swept angle is 65°. The AOA's are 15°, 20°, 25° and 30°. Five measuring section ratio of the chord length are 30%, 40%, 50%, 60% and 70%. The two models were made of brass plate through NC machine cutting. The surface of the model was attached with black paper to enhance the particle image contrast pictured on camera. These models were fixed to the bottom plate via a controllable angle adjustment mechanism within a closed water-circulating channel. Its measuring cross section is 200mm×200mm. The illuminated laser thickness is about 6mm and its power is adjusted to 4W from Ar-Ion laser. The water channel was transparent at all walls to guarantee good approach of the camera and illumination laser.

3.2 PIV experimentation

Fig.6 shows the stereo PIV arrangement adopted in the present experimentation. The circulating water was tapping water(20°C) and the approaching water velocity was about 0.20m/sec. The corresponding Reynolds number with the 150mm chord length of the delta wing model was 3.0 x 104. The frame rate of the high-speed camera is fixed to 500 fps, considering the mainstream velocity and rotating vortex velocity. The present experimental condition summarized in Table 1. The tracer particle is PVC and its average diameter is 120µm. The flow images were captured by two digital high-speed cameras(1280 x 1024 pixel).

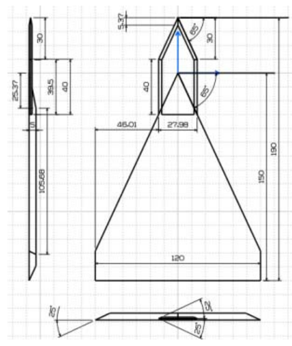


Fig. 5 Dimension of delta wing

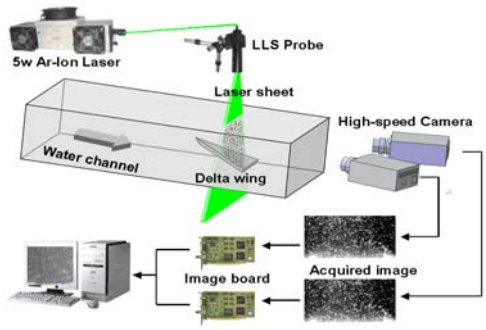


Fig. 6 PIV arrangement

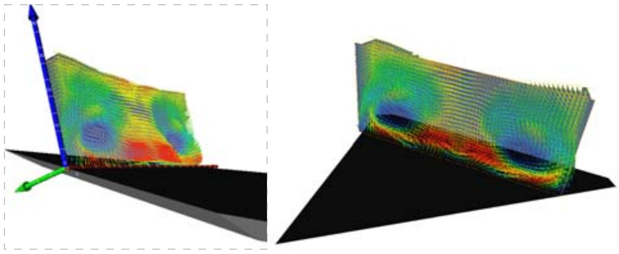
Table 1. PIV experimental conditions

Item	Specification
Working fluid	Tap water(20℃)
Particles	PVC
Host computer	Pentium 4(1.7Ghz)
Calculation time	2sec.(1000frames)
Frames for time avg.	250frames
Identification	Cross-correlation
Error ratio	Less than 1%/frame
Max. disp.	9pixels
Time interval	500Hz
Software	Cactus 3.1(IIT Co.)

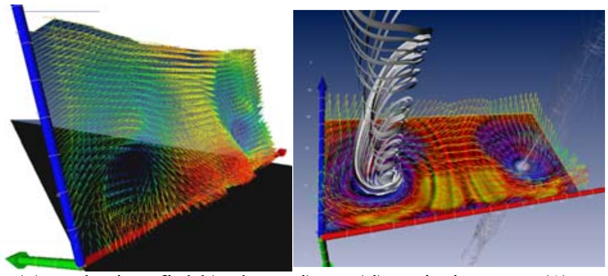
Consecutive 1,000 image frames were first saved on RAM installed in camera control board and their grey levels at the same pixel positions were averaged to produce a background image. This image was then used as a reference image data to be deduced from the gray level of any original image. This procedure was considerablyeffective to eliminate any noisy components found in flow raw images necessary in 2-D identificationprocess. Various pre-processing techniques embedded in the PIV software were performed to improve the accuracy of the identification process followed [16][17]. The cross-correlation algorithm by direct calculation of the coefficients was applied to the two consecutive images with appropriate time interval of 1/500 second. The interrogation size was 41 x 41 pixels and the maximum displacement was 9 pixels. The sampling interval was 1/500 second for the 250 consecutive data in case of the single time-averaged processing.

4. Result and Discussion

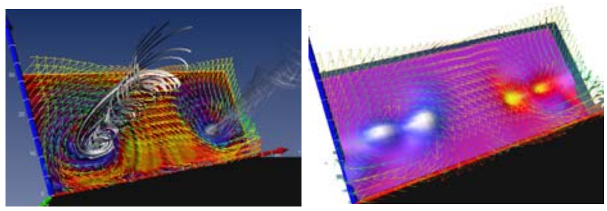
Dynamic 3D animation results are obtained from the present stereo PIV via animation software (AMIRA, www.amiravis.com). Fig.7 shows the time -averaged flows from the various perspective points. Full animation pictures are also available and they give more realistic flow behaviors unknown yet. Various viewpoints are represented for the velocity vectors from Fig. (a) to (c). Spiral wing vortex is strongly expressed by the artistic swirl images in (d) and (e). Vorticity is also shown with vector distribution in (f). Overlapped sectional streamline



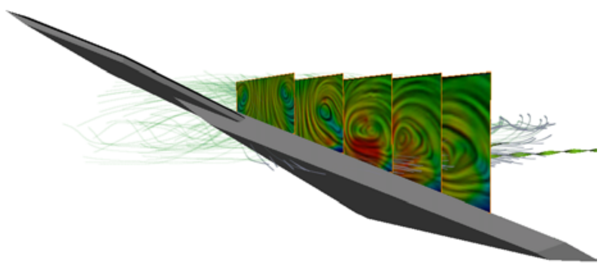
(a) velocity field(rear) (b) velocity field(front)



(c) velocity field(enlarged) (d) spiral vortex(1)



(e) spiral vortex(2) (f) vorticity



(g) overlapped sectional streamline images on the upper surface(with LEX)

Fig. 7 Sample pictures from the 3-D animation

images featuring the LEX vortex interaction are well expressed in case of LEX delta wing in (g). Two frames based 3-D stereo PIV algorithm is suggested by adopting the cross correlation identification and homogeneous coordinate system.

5. Conclusion

Homogeneous coordinate system gives an advantage of reducing the error in camera calibration by obtaining the 3-D spatial information from the image coordinates. Image transformation to correct the distorted image is also considered to guarantee the accurate stereo matching. Three camera PIV system is compared with two camera PIV system and less error vectors are generated in three camera use. 3-D dynamic stereo PIV was adopted to clarify the time-dependent characteristics of the leading edge extension(LEX) in a highly swept shape applied to a delta wing in modern air-fighters. Two high-resolution, high-speed cameras were used for the image acquisition and the stereo PIV process included the identification of 2-D velocity vectors by 2-D cross-correlation equation, stereo matching of 2-D velocity vectors of two cameras, accurate calculation of 3-D velocity vectors by homogeneous coordinate system, removal of error vectors by a statistical method followed by a continuity equation criteria. The stereo PIV represents the complicated vortex behavior, especially, in terms of time-dependent characteristics of the vortices at given measuring sections of LEX delta wing as an example. Quantities such as three velocity vector components, vorticity and other flow information can be easily visualized via the 3D time-resolved, post-processing to make the easy understanding of the LEX effect such as vortex emerging and collapse phenomena which are dominant in the field of delta wing aerodynamics.

Acknowledgement

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