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On perspective errors in endoscopic PIV

Mark Reeves [a], Nicholas John Lawson [b,*]

[a] *Lothian Imaging Sciences Ltd, 3/2 Boroughlough Lane, Edinburgh EH8 8NL, UK*
[b] *Department of Aerospace Sciences, College of Aeronautics, Cranfield University, Cranfield, Beds MK43 OAL, UK*

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Presented by Évariste Sanchez-Palencia

Abstract

Results are presented from a single and dual lens endoscopic PIV imaging system with a view to application of PIV where optical access is restricted such as internal flows. The dual lens PIV images were processed using cross-correlation, a cubic mapping function and standard stereoscopic relationships. For the single lens system, the images were processed using cross-correlation and a quadratic distortion-mapping function. Results have shown the single lens system to have in-plane errors an order of magnitude greater than the stereoscopic dual lens endoscopic PIV system. These errors are generated by perspective effects. Use of the stereo arrangement is therefore recommended wherever quantitative 3D velocimetry data is acquired using an endoscopic system. ***To cite this article: M. Reeves, N.J. Lawson, C. R. Mecanique 332 (2004).***

Résumé

Sur les erreurs de perspective dans PIV endoscopique. On présente les résultats nouveaux obtenus à l'aide d'un système d'imagerie PIV endoscopique, à lentille simple ou double , en vue d'application à la PIV (Vélocimétrie Particulaire par Imagerie) dans les situations avec accès optique direct difficile, comme dans des écoulements internes. Les images PIV à lentille duale ont été traitées en utilisant la corrélation croisée, une fonction de correspondance cubique et les relations stéréoscopiques standard. Dans le cas de du système à lentille unique, les images ont été traitées en utilisant la corrélation croisée avec fonction de distorsion quadratique. Les résultats démontrent que dans le cas d'une lentille unique, les erreurs dans le plan de vision sont d'un ordre de grandeur supérieure aux celles du système PIV endoscopique à double lentille. Ces erreurs sont engendrées par effets de perspective. De ce fait, il est recommandé d'employer la technique stéréoscopique chaque fois où les données quantitatives vélocimétriques sont obtenus avec l'utilisation d'un système endoscopique. ***Pour citer cet article : M. Reeves, N.J. Lawson, C. R. Mecanique 332 (2004).***

Keywords: Signal processing; Stereoscopic PIV; Endoscope; Perspective errors

Mots-clés : Traitement du signal ; PIV stéréoscopique ; Endoscope ; Erreurs de perspective

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[*] Corresponding author.
E-mail addresses: drreeves@aol.com (M. Reeves), n.lawson@cranfield.ac.uk (N.J. Lawson).

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1. Introduction

Particle Imaging Velocimetry is a readily available optical technique for mapping a flow from a 2D plane of interest in a fluid [1]. More recently stereoscopic PIV [2] has been intensely developed and many commercial off-the-shelf systems are now available. Stereoscopic PIV will still measure data from a 2D plane in the fluid. By using two views, however, in either an angular or translational format, 3D vector information with high accuracy can now be recovered from the planar PIV images [3].

Previous stereoscopic PIV applications have involved large scale flows with good optical access [4]. Many important applications, however, such as internal flows, high temperature and high pressure flows and flows of biological importance, can only offer very restricted optical access. This is usually because of the need to minimise geometric modifications, reduce flow interference and minimise mechanical and thermal stresses. High pulse energy beam delivery using optical fibres [5], or endoscopic relay lenses and miniature light sheet optics [6], now provide useful laser sheet illumination for internal flows with probe diameters as small as 8 mm. These advancements have resulted in several workers to adopt the PIV applications using wide-angled or endoscopic imaging systems [6,7]. This paper illustrates the significant effect of perspective errors when using endoscopic imaging systems and offers Stereo Endoscopic PIV, with suitable distortion calibration, as a method of correcting both field distortion and perspective errors.

2. Theory

A two camera stereoscopic PIV imaging system can be represented by the mapping matrix:

$$\begin{pmatrix} \Delta X_1 \\ \Delta Y_1 \\ \Delta X_2 \\ \Delta Y_2 \end{pmatrix} = \begin{pmatrix} \begin{bmatrix} F_{1,1} & F_{1,2} & F_{1,3} \\ F_{2,1} & F_{2,2} & F_{2,3} \end{bmatrix}_1 \\ \begin{bmatrix} F_{1,1} & F_{1,2} & F_{1,3} \\ F_{2,1} & F_{2,2} & F_{2,3} \end{bmatrix}_2 \end{pmatrix} \begin{pmatrix} \Delta x \\ \Delta y \\ \Delta z \end{pmatrix} \tag{1}$$

where the mapping function $F(x, y, z)$ is determined about the light sheet centreline, i.e. $z = z_0 = 0$. For a linear imaging system, the function $F(x, y, z_0)$ is represented by:

$$F(x, y, z_0) = \begin{pmatrix} -\dfrac{d_i d_0 \cos\alpha}{[d_0 + (x-h)\sin\alpha]^2} & 0 & \dfrac{d_i[d_0 \sin\alpha - (x-h)\cos 2\alpha]}{[d_0 + (x-h)\sin\alpha]^2} \\ \dfrac{d_i y \sin\alpha}{[d_0 + (x-h)\sin\alpha]^2} & -\dfrac{d_i}{d_0 + (x-h)\sin\alpha} & -\dfrac{d_i y \cos\alpha}{[d_0 + (x-h)\sin\alpha]^2} \\ -\dfrac{d_i d_0 \cos\alpha}{[d_0 - (x+h)\sin\alpha]^2} & 0 & -\dfrac{d_i[d_0 \sin\alpha + (x+h)\cos 2\alpha]}{[d_0 - (x+h)\sin\alpha]^2} \\ -\dfrac{d_i y \sin\alpha}{[d_0 - (x+h)\sin\alpha]^2} & -\dfrac{d_i}{d_0 - (x+h)\sin\alpha} & -\dfrac{d_i y \cos\alpha}{[d_0 - (x+h)\sin\alpha]^2} \end{pmatrix} \tag{2}$$

where, as shown in Fig. 1, the two cameras are separated about the object centreline by a distance h and are positioned at an angle of α to the z axes. For a non-linear imaging system, for example, caused by a distorting medium between the camera and light sheet, a direct calibration method can be used with a polynomial mapping function $F(x, y, z_0)$ such that:

$$\begin{aligned} F(x, y, z) = {} & a_0 + a_1 x + a_2 y + a_3 z + a_4 x^2 + a_5 y^2 + a_6 z^2 + a_7 xy + a_8 xz + a_9 yz \\ & + a_{10} x^3 + a_{11} y^3 + a_{12} x^2 y + a_{13} x y^2 + a_{14} x^2 z + a_{15} y^2 z + a_{16} x z^2 + a_{17} y z^2 + a_{18} xyz \end{aligned} \tag{3}$$

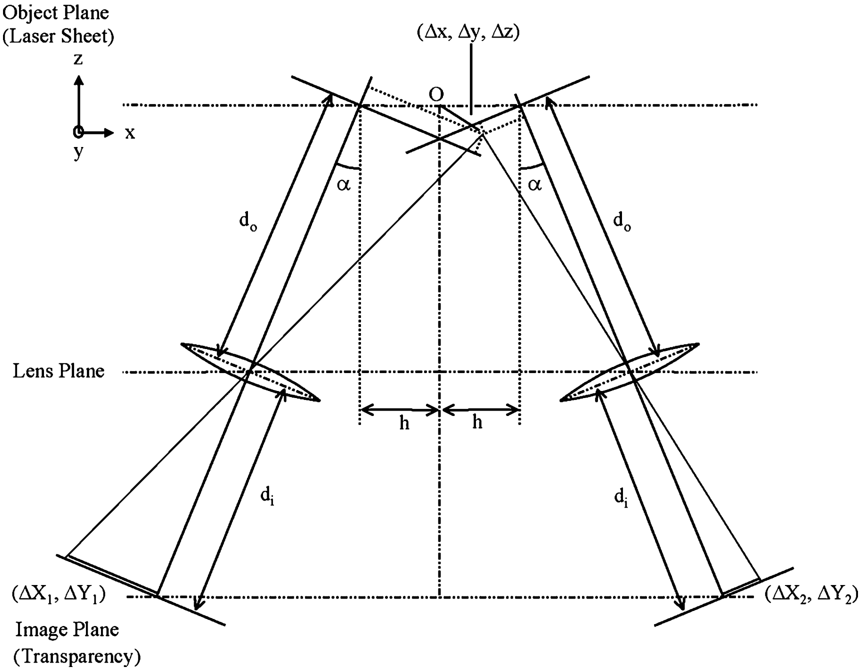

Fig. 1. Schematic of generic stereoscopic camera system.

For a single camera 2D PIV imaging system, Eq. (1) simplifies to:

$$\begin{pmatrix}\Delta X\\ \Delta Y\end{pmatrix}=\begin{pmatrix}F_{1,1} & F_{1,2} & F_{1,3}\\ F_{2,1} & F_{2,2} & F_{2,3}\end{pmatrix}\begin{pmatrix}\Delta x\\ \Delta y\\ \Delta z\end{pmatrix} \tag{4}$$

where for a linear imaging system $F(x, y, z_0)$ is represented by:

$$F(x,y,z_0)=-\frac{d_i}{d_0}\begin{pmatrix}1 & 0 & \dfrac{x}{d_0}\\ 0 & 1 & \dfrac{y}{d_0}\end{pmatrix} \tag{5}$$

In this case, the terms (x/d_0) and (y/d_0) represent the effect of perspective. For a non-linear or distorted system, however, the mapping matrix is typically replaced by a simplified function $F(x, y, z_0)$ such that:

$$F(x,y,z_0)=a_0+a_1x+a_2y+a_3x^2+a_4y^2+a_5xy+a_6x^3+a_7y^3+a_8x^2y+a_9xy^2 \tag{6}$$

As discussed previously [8] the system in Eq. (4) has three unknowns $(\Delta x, \Delta y, \Delta z)$ and only two equations. Therefore the effect of perspective, represented by terms $F_{1,3}$ and $F_{2,3}$, must be ignored for a solution to be found. As illustrated in Eq. (5), however, this will only be valid for a small field of view, i.e. when the quantities x/d_0 and y/d_0 are small. For endoscope applications, however, this is not the case since focal lengths will be short and fields of view will be large thus causing significant perspective errors. In this case the use of stereoscopic techniques will allow the removal of perspective error with accuracy now dependent on the mapping function $F(x, y, z_0)$. In what follows we present preliminary results from a twin lens endoscopic PIV system which through stereoscopic imaging will eliminate perspective error and thus improve measurement accuracy.

3. Experimental set-up

PIV test images were taken using a Pulnix CCD camera with a resolution of 1300 × 1000 pixels and an 8 mm focal length micro video imaging lens with an effective f-number of f1.8. The camera was mounted 60 mm from the object plane which was translated on an $x - z$ translation stage through an 8 mm separation to simulate a two camera endoscopic imaging system. A calibration grid with 5 mm pitch dots was translated through $z = -2.0, -1.5, -0.7, 0, 0.7, 1.5, 2.0$ mm and the images used to obtain the mapping function constants a_0–a_{18}. A simulated PIV image made from a graphite-sprayed glass slide was then backlit and translated in x and z with a displacement of $\Delta x = 0.3$ mm and $\Delta z = 0.3$ mm to obtain pairs of PIV images from the left and right camera positions. The acquisition was then repeated for a single camera position, a single calibration grid position and the same $\Delta x = 0.3$ mm and $\Delta z = 0.3$ mm PIV image translations to allow a comparison with a 2D and 3D imaging system. The data was processed using ILA VidPIV4.0 software.

4. Results and discussion

Fig. 2 shows the x–y–z displacement distributions obtained from the data processing. For the 3D processing, the average displacements were $\Delta x = 0.292$ mm, $\Delta y = 0.001$ mm, $\Delta z = -0.172$ mm with rms values of $\Delta x_{\mathrm{rms}} = 0.017$ mm, $\Delta y_{\mathrm{rms}} = 0.028$ mm, $\Delta z_{\mathrm{rms}} = -0.133$ mm. The average errors were found to be $\delta(\Delta x) = 0.017$ mm, $\delta(\Delta z) = -0.143$ mm leading to an error ratio of $e_{\mathrm{r}} = 8.45$ which compares well to a theoretical error ratio of $e_{\mathrm{r}} = 7.5$ [3].

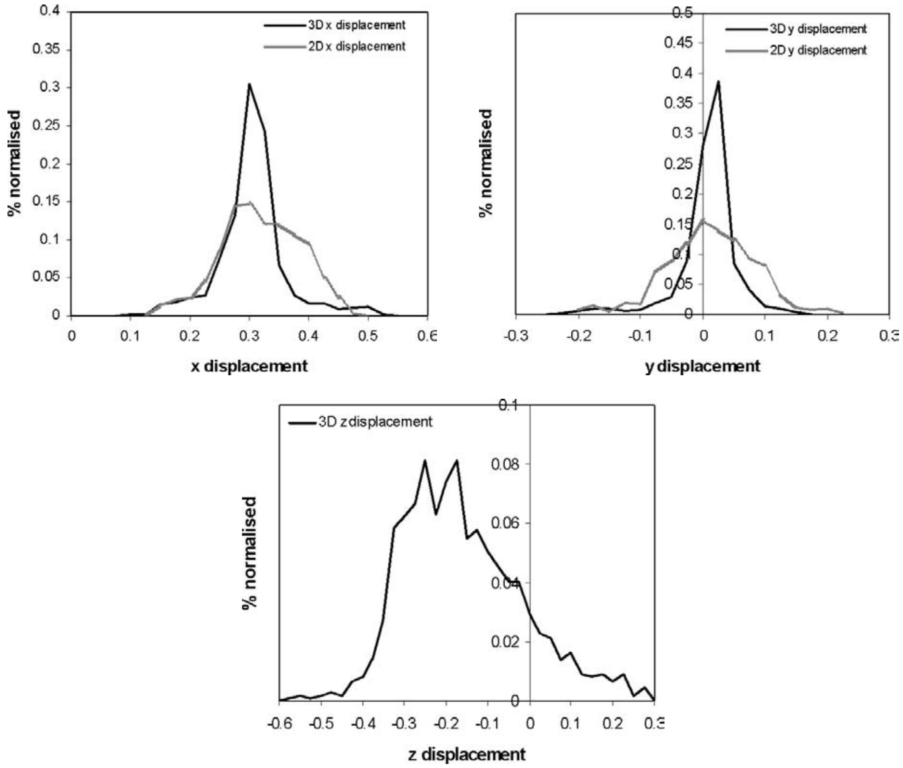

Fig. 2. Displacement distributions for 2D and 3D analysis ($\Delta x = 0.3$ mm, $\Delta z = 0.3$ mm).

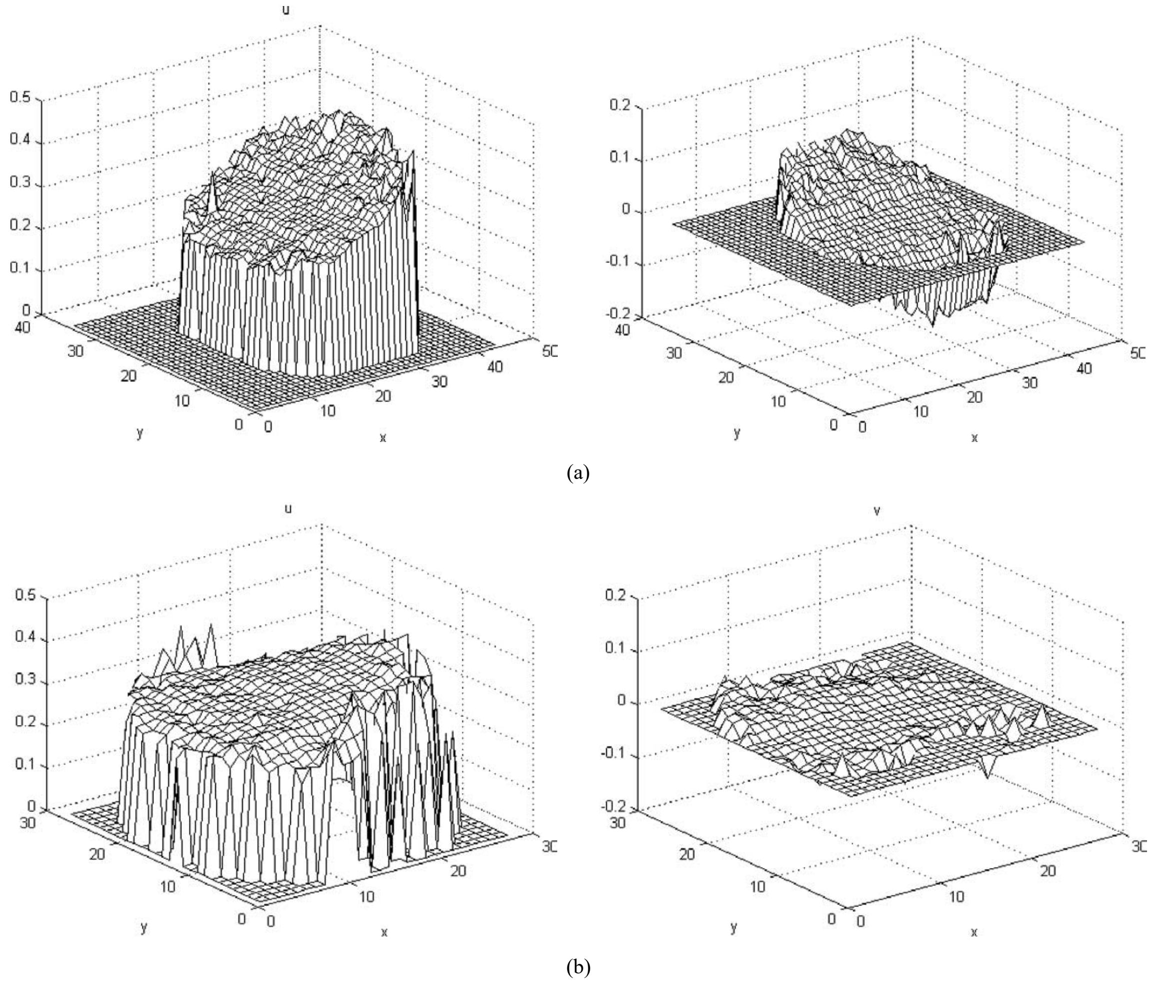

Fig. 3. In-plane (u, v) vector spacial distributions for (a) 2D and (b) 3D analysis ($u = \Delta x = 0.3$ mm, $\Delta z = 0.3$ mm, $v = \Delta y = 0$).

With reference to Fig. 2, the 2D imaging data in x yielded an average displacement of $\Delta x = 0.246$ mm with an rms of $\Delta x_{\mathrm{rms}} = 0.132$ mm, i.e. 7.8 times greater rms than from the 3D data. This increased variation is generated by the perspective error in the 2D data. This is clearly seen in the spatial distribution of the x and y displacement data in Fig. 3(a). In contrast the 3D data, shown in Fig. 3(b), does not contain this error. Also the 2D error of $\Delta x = \pm 0.1$ mm at edge of the object plane (Fig. 3(a)), matches well with the linear dependence on x/d_0 in x and y/d_0 in y which is proportional to the local z displacement. In this case the perspective error will be of order $x/d_0 = 0.33$ and $y/d_0 = 0.33$, resulting in an over or underestimation of the in-plane velocity components by over 30% where $\Delta z \sim \Delta x \sim \Delta y$.

This magnitude of perspective error is highly significant and would be expected whenever using an endoscopic 2D PIV system. This error will increase with the lens field angle, and as the ratio of out-of-plane velocity component to the in-plane components increases. Previous workers have demonstrated this limitation when taking endoscopic PIV results from an IC engine or turbine cascade [6,7]. Therefore imaging with a stereoscopic arrangement offers a practical way to correct for perspective error in arbitrary 3-dimensional flows. The stereoscopic endoscope system presented here has successfully demonstrated the capability to eliminate this perspective error.

5. Conclusions

The preliminary experiments have shown that using a simple translational stereo endoscopic system allows the in-plane velocity errors in typical endoscopic PIV measurements to be reduced an order of magnitude. Currently the out-of-plane component cannot be estimated with high accuracy owing to the high error ratio configuration. The out-of-plane component direction, however, can be retrieved and this will be useful in many 3-dimensional internal flow studies such as IC engine flow mapping. It is hoped that further work using multiple lenses and alternative calibration procedures may give further improvements in the z error.

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