Technical notes

Improving the accuracy and resolution of particle image or laser speckle velocimetry

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1 Introduction

Particle Image Displacement Velocimetry (PIDV) or Laser Speckle Velocimetry (LSV) is a non-intrusive 2-D method of obtaining instantaneous fluid velocities over an extended region. This method involves lighting a particle seeded flow with a sheet of light (usually from a laser) and photographing the particles at two instants of time on the same film. This film is then analyzed to determine the displacement of the particle over the known time interval.

Applications of PIDV and LSV have been diverse, including flow past cylinders and airfoils by Lourenco et al. (1986) and Smith et al. (1986), transient Benard convection by Simpkins and Dudderar (1978), vortex pairing in jets by Meynart (1983) and internal gravity waves by Gärtner et al. (1986). These studies however, have all been two dimensional. The velocities along the lighted plane were measured, from which the two dimensional vorticity fields and streamlines were calculated using finite differencing (Lourenco et al. 1986, and Smith et al. 1986).

2 Errors in PIDV/LSV

Apart from obvious discrepancies caused by time and space averaging in finite differencing, as well as inaccuracies due to the inability of the seeding particles to follow the flow accurately, presently used PIDV and LSV techniques have two major sources of error.

2.1 Errors in 2-D measurement of 3-D flows

As indicated by Smith et al. (1986), 2-D PIDV or LSV can give rise to significant errors in measurement if the flow is three-dimensional. The reason being, the motion of a particle perpendicular to the lighted sheet gets recorded as an in-plane displacement on the film, when the location of the particle is not on the optical axis of the camera lens.

Let P_I; $(x, y, 0)$ and P_F; $(x+\Delta x,\ y+\Delta y,\ \Delta z)$ be the initial and final positions of a particle, as shown in Fig. 1. I and F are the initial and final positions of the images respectively. Distances d_0 and d_L are measured from the optical center of the imaging lens along the optical axis (z axis in Fig. 1). Δx_m and Δy_m are the measured components of the displacement of the image along the x and y directions. Using the geometrical construction (i.e., drawing lines LAB, P_FA, AC and AD) shown in Fig. 1, the observed error in the x-displacement of the particle, due to a displacement in the z direction, is seen to be ε_x. From the similarity of triangles ABD and LCA, we have:

$$\varepsilon_x = \Delta z\,(x+\Delta x)/(d_0-\Delta z)\,. \tag{1}$$

The x-displacement of the image is given by:

$$\Delta x_m = -M(x+\Delta x+\varepsilon_x)+Mx \tag{2}$$

where M = the magnification of the imaging lens.
Equation (1) can be rewritten as:

$$\Delta x_m = -M(x+\Delta x)\,[1+\Delta z/(d_0-\Delta z)]+Mx\,. \tag{3}$$

Similarly, it can be shown that,

$$\Delta y_m = -M(y+\Delta y)\,[1+\Delta z/(d_0-\Delta z)]+My\,. \tag{4}$$

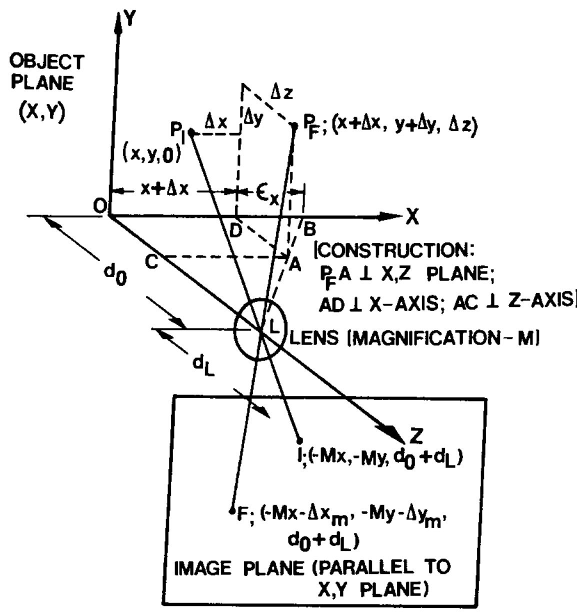

Fig. 1. Errors in 2-D measurement of 3-D flows using PIDV or LSV

The term $\Delta z/(d_0 - \Delta z)$ causes errors in two-dimensional measurements of velocities in three-dimensional flows, as shown initially by Smith et al. (1986).

This effect can be minimized by reducing the thickness of the lighted sheet and by limiting the angle of view of the camera lens, but is never completely eliminated for 3-D flows. Moreover, limiting the thickness of the lighted sheet will lead to large data dropout if the velocities perpendicular to the lighted plane are significant.

2.2 *Errors due to refraction*

When *PIDV* or *LSV* is used to study flows in fluids having a different refractive index compared to air, light scattered from the particles gets deflected at the fluid interface before reaching the imaging lens. This leads to a slight displacement in the position of the recorded image. This displacement can be significant for particles away from the lens optical axis. A review of literature indicates a lack of acknowledgement of this phenomenon for computing particle positions and displacements from the images.

A technique for eliminating these errors is presented here.

3 Correction for 3-D effects

Errors due to flows perpendicular to the lighted plane (or slab) can be eliminated by using two cameras for obtaining a stereoscopic view as shown in Fig. 2. Subscripts 1 and 2 are used to denote the images formed by lenses 1 and 2 respectively. If both lenses have the same magnification "M", Eq. (3) and (4) can be used to determine the displacements of the images formed by each lens. Combining these equations and manipulating terms, we obtain:

$$\Delta z = d_0/[1 + MS/(\Delta x_{m1} - \Delta x_{m2} + MS - S)], \quad (5)$$

where S = distance between lens centers.

Substituting Eq. (5) into Eq. (3) and (4) applied to each lens, Δx and Δy can be determined. Since no approximations were used to derive these equations, they can also be used to determine the physical locations of particles with reference to the co-ordinate axes, from the positions of the images. Hence, this method not only eliminates errors due to 3-D effects but also enables determination of all three components of velocity.

4 Correction for refraction

If the fluid under investigation has a refractive index "n" compared to air, the distance d_0 in Eqs. (1)–(5), has to be estimated taking the refraction into account.

Let

$$d_0 = d_1 + d_2, \quad (6)$$

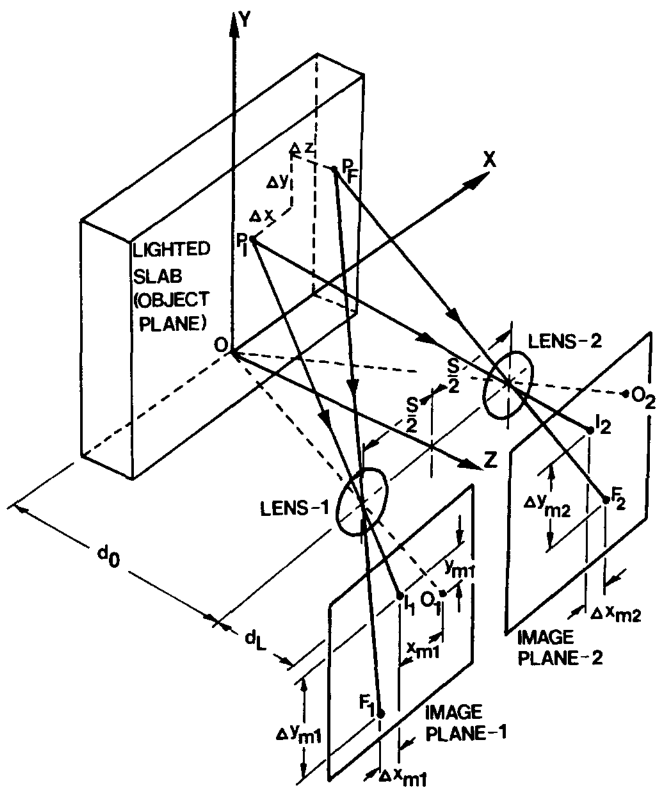

Fig. 2. Theoretical basis of stereoscopic 3-D PIDV/LSV

where d_1 = the actual distance within the test fluid, and d_2 = the actual distance in air.

However, because of refraction, the imaging lens sees the distance d_1 as d_a. If the light ray reaching the imaging lens makes an angle less than ten degrees with the fluid interface, then within an error of 0.2%,

$$d_a = (d_1)/n. \quad (7)$$

This represents a first order approximation. Hence, d_0 in Eqs. (1)–(5) has to be replaced by $(d_2 + d_1/n)$. The analysis presented above does not include corrections for refraction through container walls. This can however, be accounted for in a similar fashion.

References

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