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Holographic Diffraction Image Velocimetry for Measurement of Three-Dimensional Velocity Fields

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In recent years, much effort among fluid dynamicists has been directed at the development of experimental measurement techniques capable of accurately providing quantitative velocity information for globally transient flows. Toward this aim, a new optical nonintrusive method for the gross-field measurement of three-dimensional three-component flows has been developed and tested. Termed holographic diffraction image velocimetry, it is based on double-exposure dual-reference-beam holographic capture of particle-seeded flow-fields and the subsequent processing of time-sequence image data obtained from a single observation direction. The technique uses variable-size transplacing-window cross correlation together with an image cross-product method to extract in- and out-of-plane particle displacements from the particle diffraction images. Preliminary experiments have shown that the method can resolve fine in-plane motions limited only by the finite pixel size of the image digitizer and the magnification of the imaging system used. For out-of-plane motions, resolutions measured with a relatively unsophisticated setup have been shown to be on the order of two-tenths of the illumination wavelength divided by the square of the effective angular aperture of the system, which represents the image decorrelation distance. This is a significant improvement over other techniques, which generally can only produce lower out-of-plane resolutions.

Introduction

ACCURATE and efficient analysis of flowfields of an increasingly complex and widening scope is a necessity in modern fluid dynamics. This is especially true for transient three-dimensional three-component (3-C) flows involving such phenomena as turbulence and vortices commonly found in many aerodynamic environments. Such flows generally involve a broad range of three-dimensional 3-C velocities over a large spatial domain, making instantaneous gross-field evaluation difficult with existing point probes. Two-dimensional two-component measurement methods, such as particle imaging velocimetry (PIV), can provide valuable information but still pose limitations for investigating three-dimensional flowfields. A trend in the recent research aimed at flow measurement has been the exploration of holographic imaging techniques to extend the measurement scope to three-dimensional 3-C flows. Such methods have typically involved the use of multiple in-line holograms scanned from orthogonal directions.[1,2] Although these systems have the benefit of three-dimensional velocity extraction, they also require involved experimental setups and have limitations such as low signal-to-noise ratio due to increased speckle effects, the requirement of low-density particle seeding, lack of control in reference-to-object beam ratio, setup geometry constraints, etc. Especially, the inability to separate the reconstruction and conjugate waves from the object wave greatly contributes to the speckle noise. These adverse conditions can considerably hinder the performance in spatial resolution, dynamic range, and accuracy. In addition, in-line systems are restricted only to a forward-scattering geometry, which limits the flexibility in test section beam illumination.

In an effort to overcome the intrinsic limitations of in-line holographic techniques to broaden the measurement capability in three-dimensional 3-C velocity extraction, we have developed an off-axis holographic technique termed holographic diffraction image velocimetry (HDIV). It is based on dual-reference-beam double-exposure holography for capturing time-sequence three-dimensional particle images on a single holographic plate. Thus, it can provide the capability of measuring instantaneous three-dimensional 3-C velocity fields from a single observation direction. In the HDIV, each individual scene is independently reconstructed and scanned section by section with a solid-state camera without requiring specific particle focusing. Intensity data from independently reconstructed and digitized local particle fields are then computationally processed by employing statistical correlation algorithms for matching local sections in the time-sequence three-dimensional images to extract velocity components. Although the processing of three-dimensional images is computationally intensive, the statistical image processing can be made very efficient with modern computational hardware and software. Briefly, it is believed that the HDIV technique can provide good measurement accuracy with high spatial resolution and wide dynamic range for three-dimensional flow diagnostics.

Description of Method

An intrinsic property of hologram formation is the ability to store multiple independent images on a single recording plate if the incidence directions of the reference beams are changed between exposures. Each individual scene can then be separately recreated using the corresponding reconstruction beam without overlap (cross talk) of the other images, provided that the reference or equivalently reconstruction beams are separated by a sufficiently large angle. The HDIV system thus relies on this ability to capture multiple particle images, which can be independently viewed and compared for the extraction of 3-C particle displacements.

Figure 1 shows a typical HDIV configuration for hologram recording and reconstruction with two reference beams and a particle-field illumination beam. Although not shown here, appropriate beam splitting and expanding optics are used to produce the particle-field illumination beam and two reference beams, which can be situated at equal but opposite angles to the optical axis in most applications. Because the images are recorded in three dimensions, the illumination beam is not restricted to any specific plane of focus as in PIV and can be reasonably thick to provide true volume illumination. An initial exposure of the field is made using reference beam R_1, and after a short time of known duration, a second exposure is made of the displaced particles using the remaining reference beam R_2. After processing, the hologram is returned to its original position for image reconstruction. A solid-state camera and magnifying optics mounted on a high-resolution translation stage are used to scan individually reconstructed particle fields section by section. At

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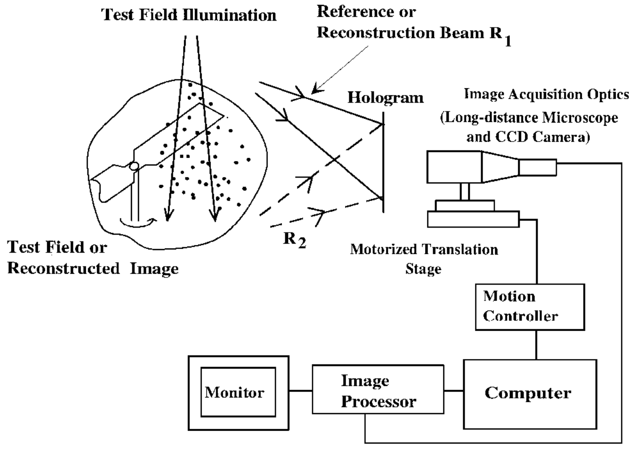

Fig. 1 HDIV configuration for hologram recording, image reconstruction, and data processing.

each section, particle displacements are extracted using a volume-image sampling and interrogation-window-matching algorithm as follows. First, a small image section window for interrogation is selected from the initial volume image using reconstruction beam R_1. The displaced particle field is then reconstructed using reconstruction beam R_2, and a matching section is found from a search volume whose cross section is larger than the interrogation plane window. Here, we assume that the interrogation plane window is small enough that all particles with identifiable diffraction patterns appearing in it have been equally displaced. The search can be carried out by finding the location of the peak of the two-dimensional cross correlation (CC) of the two images given by

$$C(u, v \mid w) = \iint I_{W_1}(x - u, y - v, 0) I_{W_2}(x, y, w)\, dx\, dy$$

$$I_{W_1}(x, y, 0) = I_1(x, y, 0) W_1(x, y) \qquad (1)$$

$$I_{W_2} = I_2(x, y, z) W_2(x - \Delta x_i, y - \Delta y_i, z - \Delta z_i)$$

where C, I_1, W_1, I_2, and W_2 are correlation value, initial particle-field image, interrogation plane window of the initial image (here, located at the origin for simplicity), displaced particle-field image, and transplaced search volume window centered at a predetermined displacement estimate $(\Delta x_i, \Delta y_i, \Delta z_i)$, respectively. The position (u, v, w) for the maximum correlation corresponds to the displacement of the image elements (particle diffraction patterns) in W_1.

For computational efficiency, a dual-aperture process is applied, which finds the in- and out-of-plane displacements separately. First, the imaging aperture is narrowed to ensure a sufficient depth of field such that diffraction due to any out-of-plane displacement is minimized in the search volume. Two plane image sections are then acquired, that is, one for W_1 and one located in the middle of the search volume. The in-plane displacement $(\Delta x_a, \Delta y_a)$ is then found at the peak of the two-dimensional CC of the two image sections. Once the in-plane motion has been determined in the search volume, a larger imaging aperture is used and a new image at W_1 with a short depth of focus is acquired by using R_1. Switching reconstruction beams once again, multiple diffraction images of the displaced field are acquired with R_2 at known locations along the optical axis, fixed at the accurate measured in-plane displacement $(\Delta x_a, \Delta y_a)$. Each image section is then analyzed through a simple image correlation operation of cross product (CP), that is, direct comparison with the initial image section W_1 to determine the out-of-plane particle displacement. Once values for the velocity components are determined, knowledge of the time between exposures allows calculation of actual particle velocities. The transplacing window technique allows selection of small search windows. Because only the two-dimensional CC operation is somewhat computation intensive, the overall HDIV processing time can be made at least comparable to that of conventional PIV for each interrogation location. The analysis of individual time-sequence scenes can allow enhanced measurement performance in nonambiguity of velocity sign, dynamic range, spatial resolution, and accuracy, as compared with autocorrelation processing of superimposed images based on photographic imaging in conventional PIV.[3] In the HDIV, the off-axis holographic recording allows freedom in test-section illumination in capturing three-dimensional scenes while the CC and CP operations provide velocity information extraction from a single observation direction.

The accuracy for in-plane components is limited by the finite pixel size of the solid-state imaging array and system magnification, whereas the accuracy of the out-of-plane component is dependent on a number of factors related to the particle size and scattering direction,[4] image acquisition optics, and scanning hardware resolution. The HDIV system provides a large effective angular aperture θ that is determined by the smallest value among scattering lobe angle of the particles, subtended angle of the holographic plate, and angular aperture of other optical components. It can be shown that the in-plane resolution d and half-depth-of-field $\Delta\ell$ of the HDIV system corresponding to the smallest identifiable image structure and image blurring distance, respectively, are given in object space dimensions as

$$d \approx \lambda/\theta \qquad \text{and} \qquad \Delta\ell \approx d^2/\lambda \qquad (2)$$

where λ denotes the illumination wavelength.[5,6] With its large effective aperture, the HDIV can produce a three-dimensional particle field with high resolution and short depth of field, ideal for distinguishing small particle displacements that might be problematic with other techniques.

In the HDIV, hologram recording requires two laser pulses in quick succession, and accurate velocity extraction can be compromised by the distortion produced if the hologram is reconstructed with a different wavelength. To produce two narrow pulses with adjustable spacing, a single double-pulsed laser such as ruby or Nd:YAG lasers can be typically employed. Until recently, however, there did not exist inexpensive high-power continuous wave (cw) lasers that shared the same wavelength as pulsed lasers for hologram reconstruction. Pulsed lasers with reasonably high repetition rate, beam quality, and power for hologram reconstruction are now possible with Nd:YAG lasers but are expensive. Rapid advances in semiconductor-laser technology in recent years, however, have resolved this hologram reconstruction problem. Currently, relatively inexpensive diode or diode-pumped lasers are readily available as reconstruction sources in a wide range of wavelengths, which can be matched to pulsed Nd:YAG or ruby lasers. The power of these lasers might be limited, resulting in weak images. This problem can be resolved by employing intensified or integrating charge-coupled device cameras, whose costs have become very economical.

Experimental Results

To validate the method and test its performance, simple experiments were performed using spherical particles 10 mm in diameter dispersed on a plane surface or in a volume. For these tests, cw illumination from an argon-ion laser was used. For the plane field measurements, a sheet beam of about 3 cm in thickness was directed nearly parallel to the surface for particle illumination. The two reference beams were situated symmetrically on either side of the optical axis at an angle of about 30 deg. After the first exposure, the plane was rotated by a small angle about the optical axis as well as about the vertical axis. These rotations thus produced known particle displacements increasing with distance from the center of rotation. Using the HDIV setup, the entire particle field was captured twice on a holographic plate, before and after rotation of the plane. After hologram processing and reconstruction, interrogation volumes measuring approximately 0.5×0.5 mm in the x–y plane were analyzed at 5-mm intervals, starting at the center of rotation and extending horizontally for a distance of 60 mm, even though the interval of data points could have been further reduced through finer data sampling. Figures 2a and 2b show the normalized in-plane CC and out-of-plane CP results, respectively, for a search volume 5 mm from the center of rotation. Both plots demonstrate an easily detectable signal peak corresponding to the respective particle displacement. By performing the CC and CP operations at many points, the in- and out-of-plane motion components were determined for the

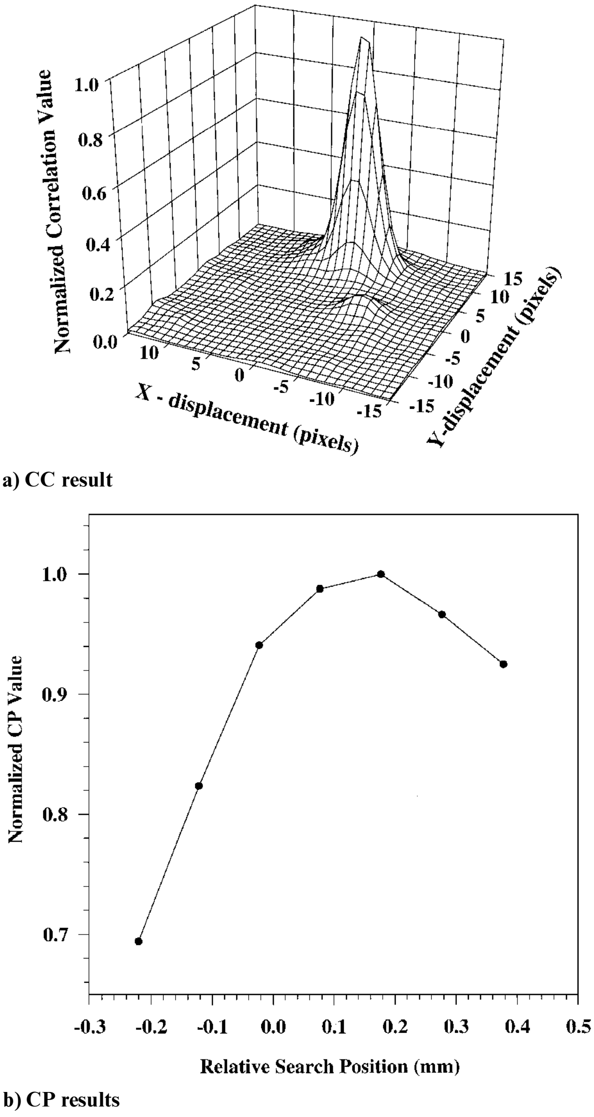

Fig. 2 Image correlation results for 3-C particle motions.

entire particle field. Both measured motions showed a high degree of accuracy. The in-plane displacements matched the known values with a standard deviation of less than one pixel, or about 1 μm, whereas the out-of-plane results, measured in units of d^2/λ (one-half depth of field) showed a standard deviation of about $0.2d^2/\lambda$, both in object space dimensions without interpolation in the correlation peak detection and using a relatively low-resolution translation stage. This corresponds to an out-of-plane uncertainty of about 10 μm, assuming θ of 0.1 rad and $\lambda = 0.5$ μm.

To investigate out-of-plane motions in a more realistic field, the 10-μm particles were suspended in a $20 \times 20 \times 80$ mm cell containing clear acrylic resin, which was allowed to harden. The cell was placed on a horizontal rotation stage such that the center of the cell was located about 60 mm from the rotation axis. Between exposures, the stage was rotated 0.57 deg producing predominantly out-of-plane particle motions. Data were collected at various search volumes along a horizontal scanning direction, covering a distance of about 64 mm. At each section, the CP operation was employed, which produced out-of-plane measurements with a standard deviation of about $0.36d^2/\lambda$ in error. The slight decrease in accuracy for these measurements as compared to the plane particle field may be due to optical nonuniformities in the acrylic, i.e., refractive index, which can distort the particle images. However, these results demonstrate the HDIV ability to resolve out-of-plane particle motions with a reasonable degree of accuracy.

Conclusion

Although the HDIV is in a developmental stage, initial experimental results have shown it to be a promising method for accurate three-dimensional 3-C velocity extraction. With current investigations focusing on further improving processing efficiency and measurement performance for practical applications, it is believed that the HDIV method can become an important flow diagnostic tool with the ability to meet the increasing demands of modern flow research. The advantages of the HDIV technique include greater experimental freedom including particle illumination direction and interrogation volume thickness. Unlike in-line holographic techniques based on direct forward scattering, which require large particle seeding at a low concentration to produce a sufficient reference/object beam and signal/noise ratios, near-forward scattering can be utilized in the HDIV. If so, the use of small particles at a high concentration with low illumination power is possible. As compared with conventional two-dimensional techniques, no specific particle focusing is required during recording or acquisition and the method allows postcontrol of reconstructed image parameters, i.e., magnification and aperture size for image resolution and depth of field, respectively. The use of CC for in-plane measurements enhances the data processing performance including velocity sign ambiguity associated with autocorrelation of superimposed images in conventional PIV. However, the HDIV also needs to effectively deal with speckle noise in coherent imaging.

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