

Whole-Field Holographic Measurements of Three-Dimensional Displacement in Solid and Fluid Mechanics

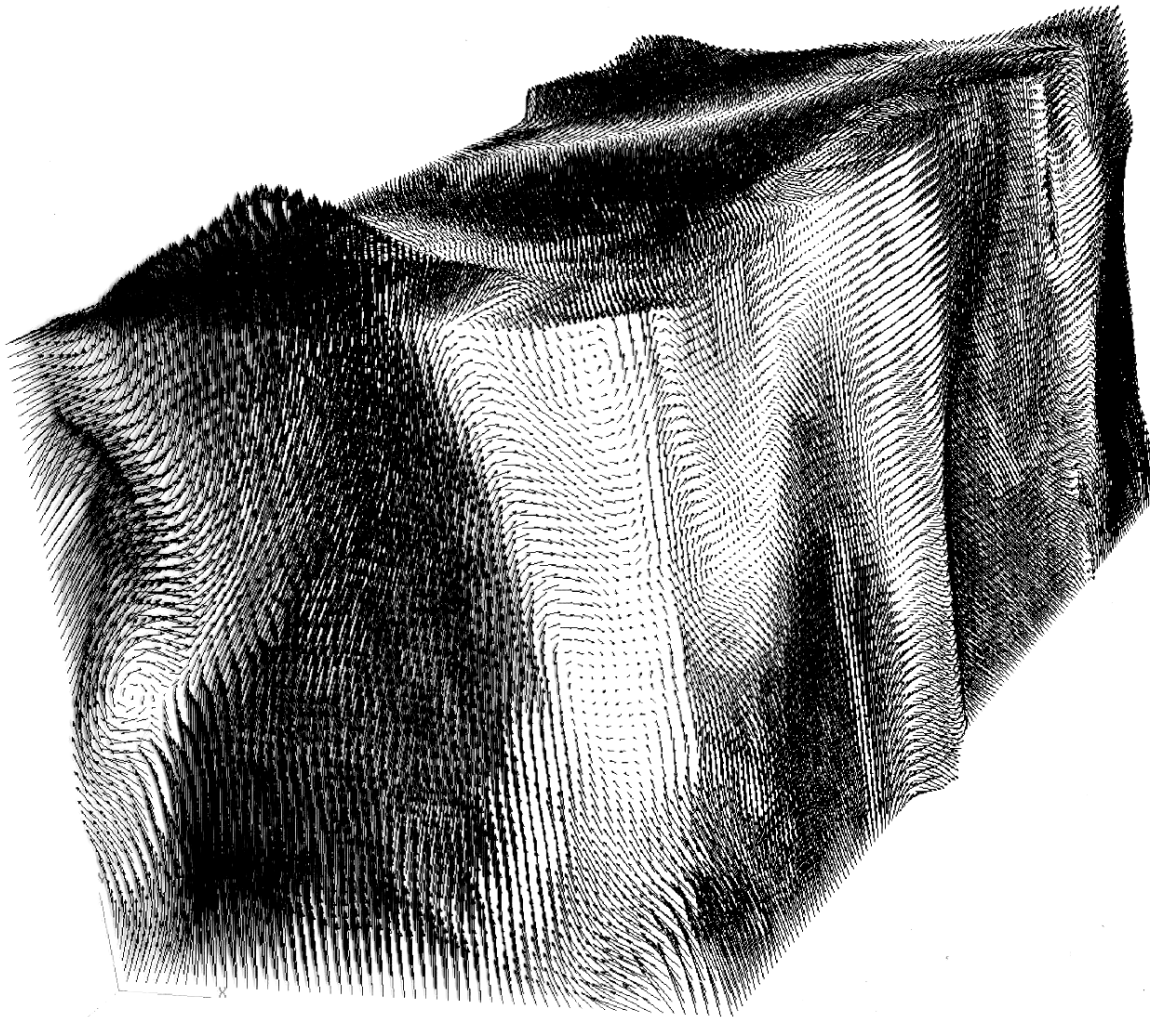
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■ Thesis Summary

There are many important engineering problems in which a process or component behaviour is highly dependent upon fluid and solid dynamics e.g. aerodynamic flutter and artificial heart valves. Typically these situations exhibit highly complex behaviour that are difficult to simulate numerically and we need experimental data to improve our understanding. Holographic velocimetry (HV) is the only experimental method capable of measuring the instantaneous, three-dimensional velocity field in a flow at millions of points in a volume simultaneously. The task of holographic velocimetry is to follow the movement of millions of micron-sized particles suspended in a flow between two or more instants in time. These neutral-buoyant "seed" particles are carried by the flow while acting as point sources that scatter the light and enable us to image the flow movement. By examining the holographic image of each particle from two viewpoints, in principle, we can triangulate on the three-dimensional particle positions at each time instant. Finally, by measuring every particle displacement between two recorded time instants and by knowing the time interval between exposures, we can determine the quantitative, three-dimensional velocity field as shown in Figure 1. The biggest challenge in HV is to automate this into a process that is fast, accurate, and robust. This thesis reports on the development of two, conceptually different, holographic systems for the 3-D measurement of displacement and velocity.



Extracted three-dimensional velocity-field data from a recorded hologram.

Figure 1

The first approach reported is holographic particle image velocimetry (HPIV). It is an intensity-based holographic velocimetry system that employs an off-axis reference-multiplexed, transmission hologram geometry with digital cross-correlation image processing and stereo-camera optics to determine the three-dimensional velocity field. The pulsed-laser holographic system produces three-dimensional images with resolution, signal-to-noise ratio, accuracy and derived velocity fields that are comparable to high-quality two-dimensional photographic PIV (particle image velocimetry). The high image resolution is accomplished by using low f -number optics, a fringe stabilized processing chemistry, and a phase-conjugate play-back geometry that compensates for aberrations in the imaging system. This HPIV system is used to measure the volumetric, three-dimensional velocity field in air seeded with micron-sized oil droplets. In the experimental result shown in Figure 1, for the first time, nearly 0.5 million three-dimensional velocity vectors have been successfully measured throughout a $24.5 \times 24.5 \times 60 \text{ mm}^3$ volume of a flow. In this result, the vectors have their mean velocity subtracted (0.8 m/s). The full measurement procedure for this result required 10 hours to carry out, most of which was spent during the interrogation processing phase that operated automatically.

The second approach, "object-conjugate reconstruction" (OCR), unifies the disciplines of holographic interferometry (HI) and holographic velocimetry. Equally applicable to fluid and solid mechanics, OCR enables quantitative three-dimensional displacement measurements between two holographically recorded events from either particle or surface scattering sites, working with either pulsed or continuous-wave laser systems. The resulting measurements taken with OCR exhibit a sub-wavelength accuracy corresponding to interferometric systems, but with a dynamic range found with PIV systems. Most importantly, the OCR design introduces the novel use of an optical fiber to specify the object measurement points. In this process, an optical fiber is used to probe the recorded object space at each three-dimensional measurement point in order to extract the three-dimensional displacement vectors. This fiber system also employs a novel optical image-shift method to eliminate directional ambiguity in the displacement measurement.

In the basic OCR technique, shown in Figure 2, a double-exposure reflection hologram is first recorded by using two identical but laterally displaced converging reference beams at two different time instants, t_1 and t_2 , shown in Figure 2(a). Then, the hologram is reconstructed using a diverging wave from a fiber-optic probe that is placed in the original object space, shown in Figure 2(b). This OCR configuration behaves as an imaging system such that a magnified image of the object in the region of the probe is produced about two fixed points in space defined by the two previous points of focus of the recording reference beams. The resulting reconstruction introduces a constant shift between exposures that provides a known bias displacement. This image shift not only resolves directional ambiguity in the displacement measurement, but is essential if the object displacement is purely in the z (longitudinal) direction.

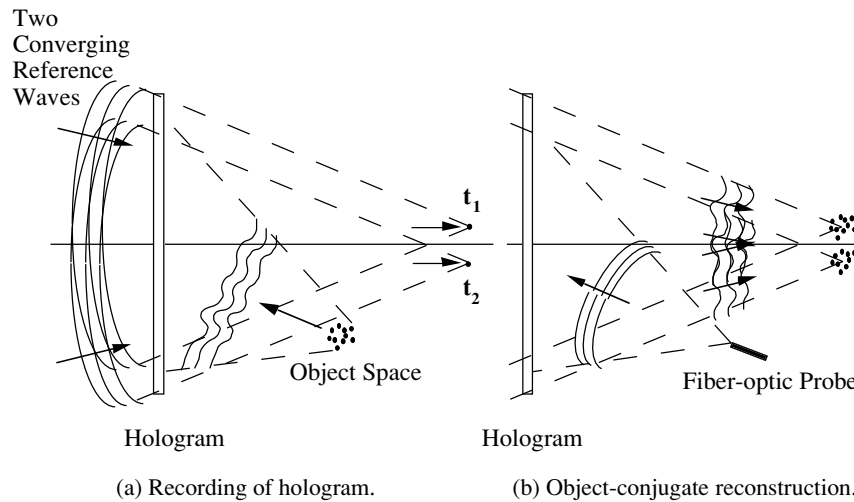
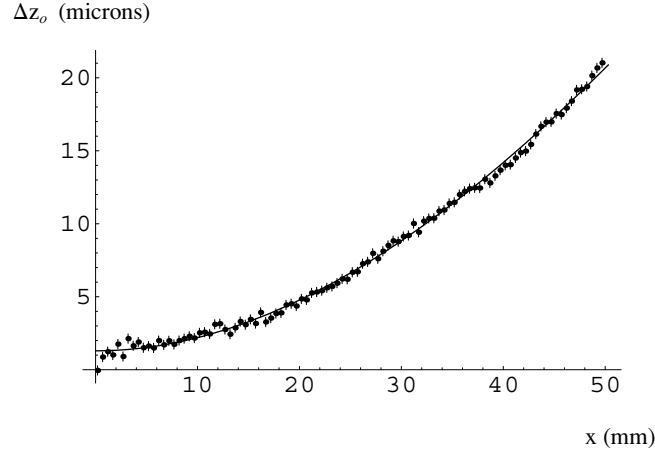


Figure 2

Furthermore, OCR uses three-dimensional complex-field correlation processing rather than two-dimensional intensity correlation of the holographic image. To accomplish this, a purpose-built optical signal processor has been developed that performs a high-speed optical Fresnel-transform of the spatial power spectrum taken from a selected object position in the OCR hologram. By correlating both the amplitude and phase information in the holographic image, the OCR system can measure spatial distributions of displacements even when the presence of severe aberrations preclude the detection of sharp images. In this way, user-friendly, simple reflection hologram geometries can be used to ensure a high numeric aperture recording for excellent depth resolution. Before OCR, the use of reflection hologram geometries were precluded.

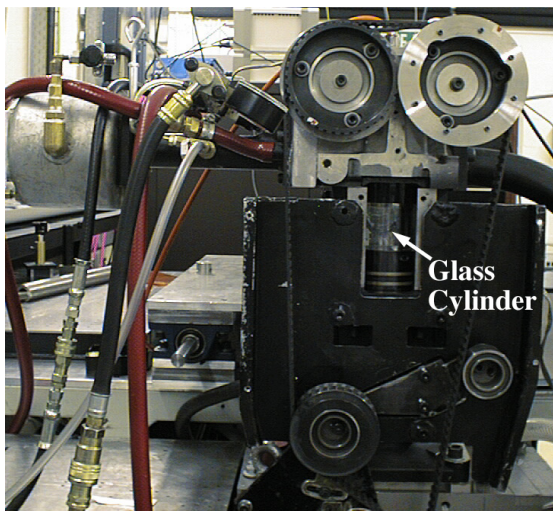
In order to experimentally characterise its capabilities, the OCR system is initially applied to three-dimensional displacement measurement in solid mechanics with a cantilevered beam experiment, reported in Figure 3. The cantilever consists of a flat plate that is fixed to a clamp at one of its ends. At a predetermined distance away from the clamp position, the plate is subjected to a predetermined displacement. This, in turn, induces a distribution of varying displacements along the length of the plate. By comparing the displacement measurement results with those predicted by cantilever theory, the OCR method reports a sub-wavelength displacement measurement resolution and a measurement dynamic range that exceeds 150:1. Unlike fringe-counting methods in HI, OCR measures absolute displacement.



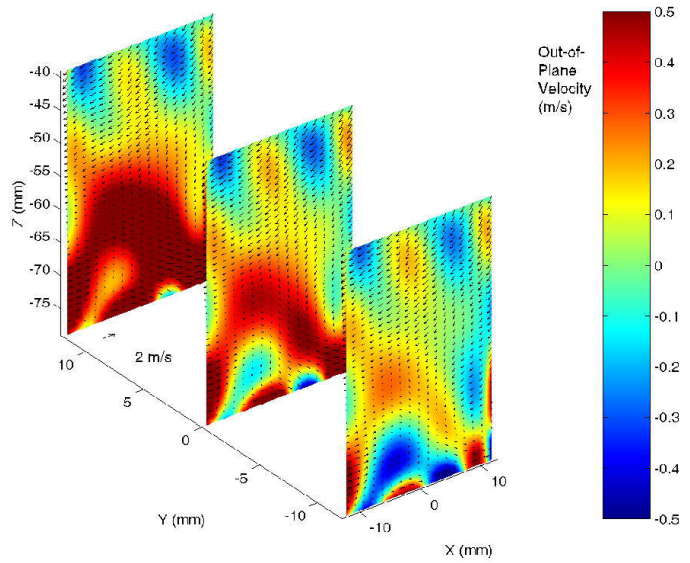
Out-of-plane displacement (points with error bars) of cantilever plotted against theory (solid line).

Figure 3

Finally, the OCR technique with pulse-laser recording is applied to fluid mechanics, shown in Figure 4. In this experiment, OCR measures, for first time, the volumetric three-dimensional velocity field of the in-cylinder flow within an internal combustion engine. Shown in Figure 4(a), the specially commissioned engine with optical access was designed and built by the Rover Group (UK) to follow the production geometry as closely as possible, including a nominal compression ratio of 10:1 and a nominal speed of 1000 *rpm*. In the flow velocity results shown in Figure 4(b), the origin is chosen to be along the bore centre-line at the height of the head gasket. The intake valves are on the right of the figure and the bulk flow at the top of the cylinder is essentially down into the cylinder. The maximum displacement measured is approximately 7 μm with a laser pulse separation of 4 μs . The principle reason for OCR's success in this application is its ability to compensate for optical aberrations caused by viewing through the transparent, thick-walled, fused-silica piston cylinder. In OCR, such aberrations are automatically removed by a holographic optical element (HOE) integral to the OCR camera design. Furthermore, as discussed previously, the complex-correlation processing used in OCR measurement is inherently tolerant of optical aberration and distortion effects.



(a) Internal combustion engine with optical access.



(b) Three-dimensional in-cylinder flow velocity data.

Figure 4