Display and measurement of complex flow fields by using digital holographic interferometry

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Introduction

Complex flow field

- Airflow and temperature induced by flame
- Atmospheric Motion
- Airflow in wind tunnel
Introduction

Complex flow field

Liquid diffusion  Bubbles motion

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Complex flow field

The motion of double droplets

Thermocapillary migration of droplets

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Introduction

How to achieve the visual, dynamical, non-destructive, high precision, full-field, quantitative measurement and display for complex flow field?
Measurement principles

Principle of digital holography

- Transparent sample
- Reflective sample
- Digital recording process of hologram

Reference beam
- Object beam
- Hologram
- CCD

Numerical reconstruction
- Numerical reconstruction of digital hologram

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Principle of digital holography

\[ \begin{align*}
O(x, y) &= O_0(x, y) \exp[i \varphi_o(x, y)] \\
R(x, y) &= R_0(x, y) \exp[i \varphi_r(x, y)] \\
I(x, y) &= |O(x, y) + R(x, y)|^2 \\
&= O^*_0(x, y) + R^*_0(x, y) + 2O_0(x, y)R_0(x, y) \cos[\varphi_0(x, y) - \varphi_r(x, y)]
\end{align*} \]

\[ \begin{align*}
U(\xi, \eta) &= -\frac{i}{\lambda d} \exp\left(\frac{2\pi}{\lambda} \sqrt{|u^2 + d^2|}\right) \\
&\quad \times F\left[R(x, y)I(x, y) \exp\left(i \frac{\pi}{\lambda d}(x^2 + y^2)\right)\right]
\end{align*} \]
Measurement principles

Principle of digital holography

Holographic image intensity

\[ I(\xi, \eta) = |U(\xi, \eta)|^2 \]

Holographic image phase

\[ \varphi(\xi, \eta) = \arctan\left( \frac{\text{Im}[U(\xi, \eta)]}{\text{Re}[U(\xi, \eta)]} \right) \]
Measurement principles

Principle of digital holographic interferometry (DHI)

1. Digital hologram $I_0(x,y)$
2. Superposition $I_0(x,y) + I(x,y)$
3. Digital hologram $I(x,y)$

- **Object wave** $O_0(x,y)$
- **Object waves** $O_0(x,y) + O(x,y)$

- **Phase distribution** $j_{00}(x,y)$
- **Interferogram** $\propto \cos^2[\pi D/2]$
- **Phase distribution** $j_{01}(x,y)$

- **Wrapped phase difference distribution** $\triangle j = j_{01}(x,y) - j_{00}(x,y) = \arg[O_1(x,y)/O_0(x,y)]$

- **Unwrapped phase difference distribution** $\triangle j(x,y)$

**Double-exposure**

**Synthetic double-exposure**

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Measurement principles

Relationship of phase difference and flow fields

Distribution of refractive index change

Assuming that the index of flow field along the optical path (z axis) is uniform, the relationship between the index and phase changes can be expressed as

$$\Delta \phi_i(x, y) = \frac{\lambda}{2\pi} (n_i(x, y) - n_0) d(x, y) = \frac{\lambda}{2\pi} \Delta n(x, y) d(x, y)$$

Then we can obtain the index change distribution

$$\Delta n(x, y) = \frac{2\pi}{\lambda} \cdot \frac{\Delta \phi_i(x, y)}{d(x, y)}$$
Measurement principles

Relationship of phase difference and flow fields

Solution concentration

The relationship between the index change and the solution concentration

$$\Delta n(x, y) = \left[ \frac{\partial n}{\partial T} \right]_{T_0} \left[ T_1(x, y) - T_0(x, y) \right] + \left[ \frac{\partial n}{\partial C} \right]_{T_0} \left[ C_1(x, y) - C_0(x, y) \right]$$

Under the condition of constant temperature, we have

$$C_1(x, y) = C_0(x, y) + \frac{\lambda}{2\pi d(x, y)} \Delta \varphi(x, y) \left[ \frac{\partial n}{\partial C} \right]_{T_0}$$

Similar ways can be used to obtain the distributions of temperature, density, velocity, as well as diffusion coefficient of flow fields.

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Applications

Experimental setup based on Mach-Zehnder interferometer

- Heat sink
- 532nm Laser
- 1×2 Coupler
- Optical fiber
- Reference beam
- BS
- CCD
- Detection beam
- L₁, L₂, L₃, L₄
Applications

Experimental setup based on Fizeau interferometer
Applications

Experimental setup based on Mach-Zehnder interferometer with dual-wavelength technique

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Application 1: Karman vortex street in water flow field

Sample for Karman vortex street generation

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Application 1

Application 1: Phase difference distribution of Karman vortex street

(a) (b) (c) (d)

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Application 2: Crystallization process in protein-lysozyme solution

Solution sample:
1:1 mixing solution of lysozyme (28mg/ml) and NaCl (35mg/ml)

Dynamic wrapped phase difference map (0~4750min)


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Application 2: Crystallization process in protein-lysozyme solution

Solution concentration variation plots during crystallization process

Measurement results of the solution concentration in the top, middle, bottom regions;

Fitting results corresponding to (a)


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Application 3: Liquid diffusion

Diffusion process between water and alcohol


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Application 4: Rayleigh-Benard convection (RBC)

Phase difference of RBC

Temperature distribution at horizontal positions

(a) 0s; (b) 20s; (c) 42s; (d) 86s; (e) 133s

Application 5: Thermocapillary of droplets

Phase difference of temperature field in liquid container

Application 5: Suspended and motion state of droplet
Application 6

Application 6: Air flow in wind tunnel

Wind tunnel model

Application 7

Application 7: Heat exchange process of air flow field near heat sink

Temperature distributions along the vertical direction in (a)-(h)

Reference:
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Application 8

Application 8: Shockwave field

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Application 9: Unstable reaction-diffusion process

Application 10: Laser ablation on the surfaces of liquid

Phase difference distributions of the ablation region

(a) Deionized water using 470 mJ energy; (b) glycerin using 470 mJ energy.

From the phase change between the two adjacent pixels in saltation process, the boundaries of cavity and jet can be detected.


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Application 11: Ultrasonic standing wave

Ultrasonic standing wave device

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Several applications of digital holographic interferometry in display and measurement of complex flow fields are presented.

Related experiment results with specially designed setups during the dynamic evolution processes of flow fields are shown.

Digital holographic interferometry is an effective tool.