G151

加熱液面の動的変形挙動の ESPI 測定
ESPI Measurement of Dynamic Surface Deformation of Heated Liquid Surface

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Measurement of dynamic surface deformation (DSD) is important for full understanding of oscillatory mechanisms of Marangoni convection in a liquid bridge. A novel method based on electronic speckle pattern interferometry (ESPI) is developed here. ESPI is widely used for displacement measurement of optically rough surfaces. The present system expands the capability of ESPI so as to measure specular liquid surfaces. Time sequence phase method is adopted for phase evaluation of specklegrams, which enables the method to measure dynamic displacement of deformed liquid surface with sensitivity of \( \lambda/4 \). Frequency analysis and comparison with previous data of DSD of liquid-bridge free surface are presented.

Key Words: Interferometer, ESPI, Surface tension, Dynamic liquid surface deformation

1. Introduction

A novel technique is needed to measure dynamic surface deformation (DSD) of liquid bridge induced by thermocapillary convection. The amplitude and frequency of DSD to be measured are submicron and about 1Hz, respectively. As the surface shape of the liquid bridge is cylindrical with noticeable deformation due to gravity, conventional interferometry designed for specular surfaces will encounter severe difficulties in preparation of suitable reference surfaces. In contrast, electronic speckle pattern interferometry (ESPI) is a versatile technique that achieves high-sensitivity real-time measurements of DSD of optically rough surfaces without requiring any special reference surfaces. We present here an accommodated ESPI system that works on optically smooth surfaces and some results obtained from DSD measurements of a liquid bridge.

2. Methods

2.1 Basics of the present ESPI system

To expand applicability of ESPI to specular surfaces, it is essential to generating speckle fields from smooth wave fronts reflected from an object surface. Fig. 1 shows a schematic of the present ESPI system. The coherent laser beam is divided into the reference and object beams by the polarizing beam splitter (PBS). Their intensity ratio is adjusted with the help of a \( \lambda/2 \) plate placed in front of the PBS. The role of the \( \lambda/2 \) plate is to rotate the polarization plane of the laser beam impinging on the PBS, thus to change the intensity ratio between vertically and horizontally polarized components. The divided beams are reflected by the reference and object surfaces. Note that both surfaces are specular. The reflected beams go through \( \lambda/4 \) plates separately and are recombined at the PBS and then imaged, by the objective lens, onto the smooth-side surface of the ground glass. The rough-side surface of the ground glass is viewed by the CCD element through the camera lens.

2.2 Principle of measurement

The irradiance at each pixel of CCD element is given by

\[
I(x, y) = |o(x, y)|^2 + |a(x, y)|^2 + 2|o(x, y)||a(x, y)| \cos[\phi(x, y)]
\]

where \( \phi(x, y) = \phi_0(x, y) - \phi_1(x, y) + \phi_{00}(x, y) - \phi_{0R}(x, y) \), \( o \) and \( a \) are the amplitudes of the object and the reference beams, \( \phi_0 \) and \( \phi_1 \) are the phases introduced by the shape of the object and the reference surfaces, \( \phi_{00} \) and \( \phi_{0R} \) are the phases introduced by the ground glass during propagations of the object and the reference beams. \( \phi_0 \) and \( \phi_1 \) should obey smooth functions while \( \phi_{00} \) and \( \phi_{0R} \) are randomly distributed. Consequently, the final image on the CCD element creates speckle patterns, from which the ESPI technique can extract information of surface deformation.

If the deformation of the object surface is small enough, we can assume that the lens still images the object surface onto the same resolution area of the ground glass as it does before deformation. Thus the phase change of the object beam observed at the CCD element is determined only by the change of the initial phase at the foreside of the ground glass, which is determined by the deformation. The irradiance viewed by the camera after deformation is given as follows:

\[
I'(x, y) = |o(x, y)|^2 + |a(x, y)|^2 + 2|o(x, y)||a(x, y)| \cos[\phi(x, y) - \Delta \phi(x, y)]
\]

where \( \Delta \phi \) is the phase change due to deformation. If the laser illuminates the object surface perpendicularly, the relationship between phase change and displacement can be simplified as:

\[
\Delta \phi(x, y) = \frac{4\pi}{\lambda} \frac{d(x, y)}{d(x, y)}
\]

where \( d(x, y) \) is the displacement distribution.

2.3 Phase evaluation

The phase evaluation is done by time sequence phase method.
(TSPM) that consists of two stages: wrapped phase calculation and phase unwrapping. For continuous deformation, the gray level distribution of specklegrams can be expressed as:

\[ I(x,y,t) = I_b(x,y) + I_m(x,y) \cos \phi(x,y,t) \]

where \( I_b \) and \( I_m \) are the background and modulation intensities of the specklegram. They are assumed to vary with time very slowly. \( \phi(x,y,t) \) is the phase value of each speckle which carries the information of deformation. It is obvious that

\[ I_{\text{max}}(x,y) = I_b(x,y) + I_m(x,y) \]
\[ I_{\text{min}}(x,y) = I_b(x,y) - I_m(x,y) \]

With enough number of specklegrams, the approximate maximum and minimum values of each pixel can be obtained and then the wrapped phase of equation (4), \( \phi_w \), can be calculated as follows:

\[ \phi_w(x,y,t) = \cos^{-1} \left\{ \frac{2(I(x,y,t) - I_{\text{min}}(x,y))}{I_{\text{max}}(x,y) - I_{\text{min}}(x,y)} \right\} \]

where \( \phi_w \in [0, \pi] \).

Phase unwrapping is done in a temporal domain. Reader should refer to [3] for more detail.

3. Experimental apparatus

The layout of the present experimental apparatus is shown in Figure 2. The light source is a diode pumped solid state Nd:YAG laser that delivers a coherent TEM_00 beam with 50mW output power and 532nm wavelength. An acromat lens (Lens A) is placed in front of the PBS to control size of laser spot on the surface of liquid bridge. An aspheric lens (Lens B) relays the free surface onto the smooth-side surface of the ground glass. A B&W CCD camera having a 2/3inch CCD array with 512x480 cells is used to image speckles generated at the rough-side surface of the ground glass. The camera is equipped with a telecentric lens having focal length of 55mm, which provides a FOV nearly of 1x1mm². A frame grabber with 768MB memory is used to capture specklegrams at 50fps for about 120 seconds consecutively. The experimental liquid is silicone oil of 5cSt in viscosity. Height of the liquid bridge is 2.5mm, and its diameter is 5mm. Volume ratio of the liquid bridge is 100%. Disk temperature difference is slightly above the critical value, and therefore the oscillatory flow field is in pulsating mode.

4. Results and discussion

Figure 3 shows gray level variation signal of a single pixel chosen and its frequency spectrum. Frequency of gray level is modulated by wavelength of the laser. With the help of microscope it is known a priori that the DSD amplitude is less than half the wavelength. Hence, the main frequency (1.17Hz) found from the present ESPI measurement is judged to be the frequency of DSD. This frequency is in agreement with 1.20Hz reported previously \[1\]. Figure 4 shows the frequency distribution in the entire image. Frequencies are mostly 1.17Hz and sometimes 2.34Hz.

5. Conclusions

A modified ESPI system is developed by implementing TSPM into the technique. The modification enables the ESPI technique to be used for the deformation measurement for free liquid surface. The present DSD measurement of liquid bridge provides results consistent with the previous study.

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References