Time-dependent Surface Response of Fluid to Transmission Optical Pressure Impulse

David C. Clark and Myung K. Kim*
Digital Holography and Microscopy Laboratory, Department of Physics, University of South Florida, 4202 E. Fowler Avenue, Tampa, Florida 33620
**Corresponding author: mkkim@usf.edu*

Abstract: Dynamic response to an optical pressure pulse can be a useful indicator of the mechanical properties of a fluid surface or membrane. We have mapped the time-dependent response of the water surface using precise measurement and timing techniques.
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1. Introduction

Measurement of optical radiation pressure effects can be a very useful tool in soft matter physics for the efficient characterization of fluid interfaces and membranes. Although it is one of the most noninvasive methods, very little work has been done in this area due to the difficulty in observing this weak interaction. The quantitative phase analysis inherent to digital holography, DH-QPM [1], offers significant advantages over traditional imaging, however, the phase image is often dominated by thermal effects. In fact, even transparent media can have a thermal effect [2], which very quickly becomes far dominant to the effect of optical radiation pressure when a continuous wave, cw, excitation source is used [3]. The effects can be successfully decoupled by the use of time-resolved DH-QPM [4], however, the final phase image will still be a superposition of the two.

In this study, we have used nanosecond pulsed laser excitation to provide a transmission optical pressure impulse to the free water surface. By replacing cw excitation with pulsed excitation, we have greatly reduced the total thermal effect to a negligible level at the time of excitation. Since the response of the fluid surface occurs on a microsecond scale, this already insignificant thermal effect has dissipated by the time measurable surface deformations are present. Additionally, the time dependent nature of such a response involves not only static characteristics of interfaces, such as surface tension, but also dynamic mechanical properties, such as viscosity. It was the goal of this study to combine a detailed time-resolved image technique with this optical pressure impulse excitation method to produce a spatiotemporal map of the water surface response.

2. Theory

As described in [3], by solving the conservation of momentum equation for the simple case of a flat interface with normal incident photons, we have for the exchange across the interface,

$$\vec{p} = \frac{2n_1}{c}\left(\frac{n_1 - n_2}{n_1 + n_2}\right) Nh\nu\hat{z} \tag{1}$$

where n_1 and n_2 are the refractive index of the first and second media, respectively and N represents the number of photons. It is easy to see from this relation that the direction of momentum transfer, and therefore the deformation of the interface, will always point in the direction of the smaller refractive index material regardless of the direction of beam propagation. The resulting phase shift will therefore always be positive, which is contrary to that of a thermal lens, making the two effects easily distinguishable by DH-QPM, though the current method of pulsed excitation eliminates this necessity.

The measured phase shift is related to physical height of deformation by,

$$\phi = h\left(n_2 - n_1\right)\frac{2\pi}{\lambda} \tag{2}$$

where *h* is a shape function describing the deformation field. In the present study, this is a time-dependent impulse response function. We are currently developing a model to describe this function as a relation to the dynamic mechanical properties of an interface such as surface energy and dynamic viscosity.

3. Methods

Figure 1 shows a diagram of the experimental apparatus. A Mach-Zehnder interferometer is used to create the hologram of the sample using low power (<1mW) 633-nm laser light. The imaging beam arrives collimated at a beam splitter that transmits half the beam into the reference arm and reflects half the beam into the object arm of the setup. The beams each follow a similar path, through matching singlet objective lenses, before recombining by another beam splitter. The interference of the phase-modulated object beam with the reference beam creates the hologram. This hologram is recorded by a digital CCD camera placed atop the setup and passed into our LabVIEW personal computer platform for amplitude and phase reconstruction based on the angular spectrum method [5].

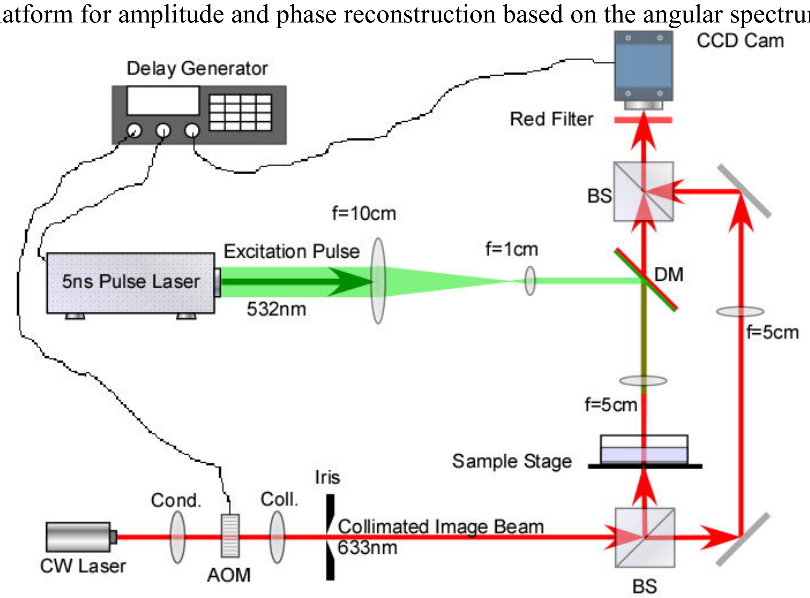

Fig. 1. Experimental apparatus. Pulsed excitation beam (green); Imaging beams (red); Microscope Objective (MO); Beam Splitter (BS); Dichroic Mirror (DM); Acousto-optic Modulator (AOM).

An integrated optical excitation arm delivers a 532-nm, 5 ns pulse laser beam to the system. The beam is passed through a 10:1 focal length lens pair to create a much reduced beam radius. A dichroic mirror reflects this excitation beam down toward the sample while allowing the probe beam to transmit up toward the CCD camera. The excitation beam passes through the shared objective lens which focuses the already narrowed beam through the sample area. The objectives are chosen to have long effective focal lengths to aid in maintaining constant beam width at the interface. A removable red bandpass filter is placed just in front of the CCD camera to filter out any 532-nm excitation light leaking through the dichroic mirror. This “leaky” light, however, can be used to profile the excitation beam by temporarily removing the green filter. The excitation beam radius is defined as the radius at which the Gaussian beam intensity reduces to e^{-2} of its maximum.

The sample consists of a partially water-filled modified glass cuvette 10 mm by 40 mm by 45 mm with a sealable lid. With the excitation beam profiled and adjusted to a desired radius via the excitation arm lenses, the sample is placed on the sample stage on its side oriented with a 10 mm path length. The water level in the cuvette is filled to a height of 5 mm in this orientation. The modified cuvette has a small (~6 mm) hole drilled through the upper glass surface providing an unimpeded excitation beam delivery. The purpose of this modification is to eliminate the occurrence of glass surface etching during excitation, yet still protect the free water surface from ambient air currents. All general phase aberration, including wavefront curvature mismatch, can be easily compensated for by storing a background phase image prior to excitation and subtracting this from the excited image.

A pulse delay generator controls precise timing of both excitation and imaging. Prior to delivery to the system, the imaging beam is condensed through an acousto-optic modulator (AOM) which, during triggering, diffracts the imaging beam through an iris and collimating lens. The pulse delay generator sends a 5 μs square pulse signal to this AOM shutter system at specified delay times relative to the excitation pulse. This delivery method produces the short exposure images required for this study without sacrificing phase quality as would be likely if a pulsed imaging beam were used instead.

4. Results and discussion

The above described apparatus and timing were fine-adjusted to achieve optimal results. The AOM shutter system was adjusted for a maximum diffraction peak into the system to maintain good intensity of the hologram for short exposures. The timing of the delay generator and the system components were confirmed using an oscilloscope. The excitation beam radius was adjusted to 90 µm at the water surface. The peak power per pulse (25.8 kW) was calculated from the average power at 10 Hz as measured with a standard power meter.

Figure 2 displays the phase shift as a function of radial distance from the center of the structure for each time step recorded. The time intervals were 5 µs up to 100 µs, then 10 µs intervals up to 200 µs, followed by 20 µs intervals up to 300 µs. Notice that as the structure grows and relaxes the center of the structure is not always the maximum. This is typical behavior in all trials and is likely the result of the dynamic fluid mechanics that will be described in our developing model. Since the structure grows in diameter as the surface relaxes, the outer edge moves beyond the current field of view soon after this. The physical deformation height at the center of the structure is plotted as a function of time in fig. 3. While this data fits very well to the trend of a previously proposed model [6], it is our near future goal to independently develop a detailed model that directly relates the response behavior to the dynamic properties of the interface.

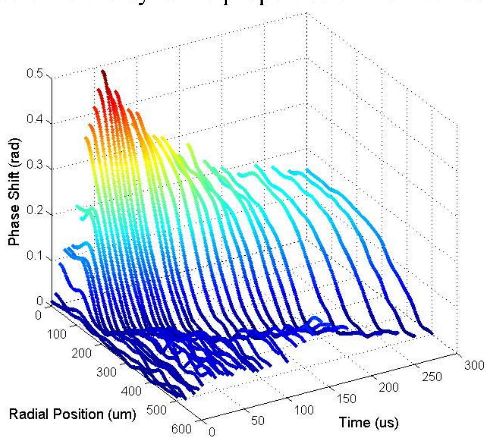

Fig. 2. Phase profile response as a function of radial distance from the center of the structure at each time interval.

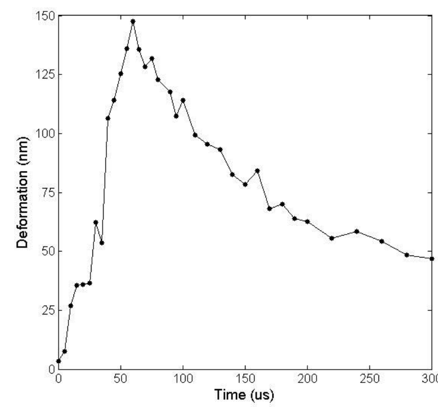

Fig. 3. Physical deformation height of the center of the structure as a function of time.

Noise levels of our system were measurement by imaging the sample without excitation and taking the standard deviation of a single cross-section to indicate background noise. Values for the raw data ranged between .01 and .03 radians during the course of these experiments. While this is impressive, the symmetry of the structure allows for the averaging of each radial point around the circumference, making full use of the array of data collected and reducing the noise level by up to an order of magnitude as described in [7]. It is, in fact, possible for the current method to distinguish deformation heights with better than 1 nm resolution.

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