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Using laser Doppler vibrometry to measure capillary surface waves on fluid-fluid interfaces

James Friend[a)] and Leslie Yeo
Department of Mechanical and Aerospace Engineering, MicroNanophysics Research Laboratory, Monash University, Melbourne VIC 3800, Australia

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Capillary wave phenomena are challenging to study, especially for microfluidics where the wavelengths are short, the frequencies are high, and the frequency distribution is rarely confined to a narrow range, let alone a single frequency. Those that have been studying Faraday capillary waves generated by vertical oscillation have chosen to work at larger scales and at low frequencies as a solution to this problem, trading simplicity in measurement for issues with gravity, boundary conditions, and the fidelity of the subharmonic capillary wave motion. Laser Doppler vibrometry using a Mach–Zehnder interferometer is an attractive alternative: The interface's motion can be characterized at frequencies up to 40 MHz and displacements of as little as a few tens of picometers. © *2010 American Institute of Physics.* [doi:10.1063/1.3353329]

I. INTRODUCTION

Capillary waves on interfaces, simple to generate and observe yet so extraordinarily intricate in mechanism and behavior, have been the source of many researchers' interest for nearly 2 centuries. Faraday[1] first described them in 1831, having found capillary waves appearing upon mercury with a frequency one-half the vertical excitation frequency, and over the years, such waves have come to be named after him[2] with increasing degrees of analysis and concurrent complexity.[3,4] Indeed, the area continues to attract interest for the rich nonlinear dynamics apparent even in experiments, leading some to examine what they term *capillary turbulence*[5] in both the temporal response of capillary waves upon a surface from vertical excitation to even unusual spatiotemporal patterning and spatially distributed turbulent behavior.[6,7]

Although others have tried controlling the appearance of such waves[8,9] or have considered more complex excitation schemes,[10] the difficulty of accurately measuring the characteristics of the wave while adequately controlling the boundary conditions has limited researchers to work on frequencies of at most a few thousand of hertz.[11] However, there are many practical applications of such capillary waves driven at far higher frequencies—a few to even several hundreds of megahertz—from the production of nanoparticles[12,13] to pulmonary drug delivery[14,15] via atomization, a process believed to occur due to Faraday wave instabilities driven to eventually eject droplets with a size roughly corresponding to one-half the wavelength of the capillary wave.[16] Therefore, by increasing the excitation frequency, f, the capillary wavelength and therefore the droplet size, d, is reduced according to $d \sim f^{-2/3}$. Unfortunately, this relationship does not hold at high frequencies and the discrepancy has been remarkable[17] with some researchers even proposing (unnecessarily, see Ref. 14) cavitation as the dominant mechanism[18,19] instead. Capillary waves in microfluidics contribute to a wide range of other phenomena, including particle rafting[20] and concentration,[21] that are physically curious and have engineering applications.[22,23] An attractive advantage of working at small scales is the ability to control the significance of gravity in the

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[a)] Author to whom correspondence should be addressed. URL: http://mnrl.monash.edu. Electronic mail: james.friend@eng.monash.edu.au.

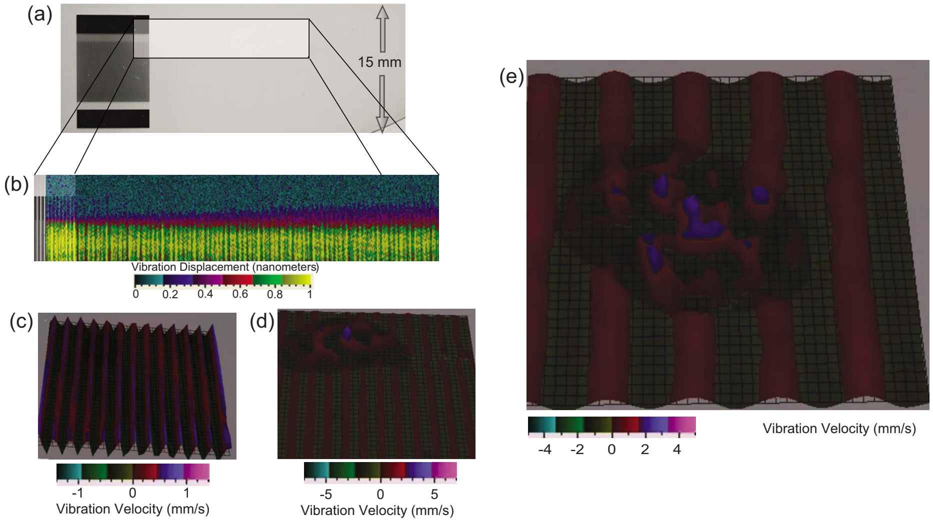

FIG. 1. Laser Doppler vibrometry of SAW and fluid interfaces driven by SAW (enhanced online). [URL: http://dx.doi.org/10.1063/1.3353329.1] (a) 30 MHz SAW device with straight electrodes generates acoustic waves (b) propagating across the substrate with a magnitude contour plot, equivalent to generating vibration velocities of several millimeters per second as shown from an oblique view of a measurement performed on a 20 MHz device, (c) without a droplet, (d) with a 5 μl de-ionized water droplet, and (e) a much closer view of a 0.5 μl droplet.

behavior of the interface[24] without resorting to microgravity[25] or even spacecraft;[26] gravity's influence scales with the volume of the fluid and thus becomes irrelevant when, for example, the size of a water sample is less than a millimeter or so. Still, the problem of accurately measuring the capillary wave at small scales—and therefore high frequencies due to the associated short wavelengths—remains.

We demonstrate in a simple case here the use of scanning, reflective Mach–Zehnder heterodyne interferometry for performing such measurements with sufficient veracity to measure capillary wave amplitude and phase response spectra over frequency ranges of a few hertz to 40 MHz, presenting some sample results with discussion and details of the method. The opportunity presented by the use of laser interferometry in interface measurement is access to a far broader frequency range for excitation and subharmonic capillary wave vibration, along with the myriad boundary conditions, geometries, fluid characteristics, and excitation possible in microfluidics.

II. RESULTS AND DISCUSSION

With a scanning laser Doppler vibrometer (LDV) that measures motion along the axis of the laser, the transverse displacement of fluid interfaces may be measured. In our approach, we have measured the transverse displacement distribution of a solid substrate surface and across the interface of a fluid droplet due to the propagation of a surface acoustic wave (SAW) as it is being excited at 30 MHz; neither the in-plane component of the Rayleigh SAW nor the resulting capillary wave can be detected.[27] Even so, much useful information can be gathered, for instance, the interaction of the propagating acoustic wave with fluid droplets, as shown in Fig. 1. Note that the wavelengths of acoustic radiation are 69 μm at 30 MHz and 100 μm at 20 MHz in water. A standing SAW in Fig. 1(b) is formed by reflection of a standard traveling Rayleigh SAW, itself formed from a single interdigital transducer (IDT) structure shown in Fig. 1(a), from the free edges at either end of the substrate. There is some noticeable absorption of acoustic radiation to the right of the 5 ml droplet in Fig. 1(d) and strong amplification of the acoustic radiation incident into a very small droplet in Fig. 1(e), producing a large capillary wave on the droplet's interface.

Some care must be used in interpreting these results, however, as the height of larger droplets [cf., Fig. 1(d)] is well outside the depth of field if one focuses on the substrate surface, giving erroneous results for the vibration amplitude. Further, there is some difficulty in taking data near

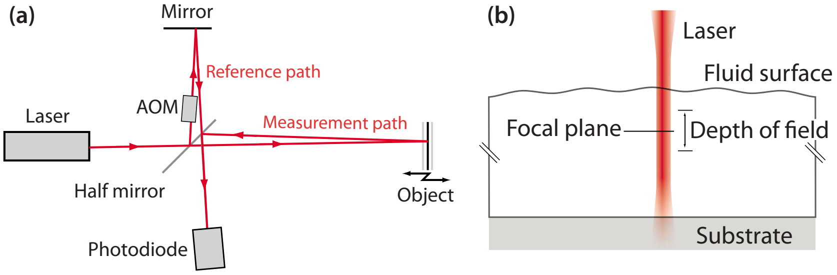

FIG. 2. Mach–Zehnder laser Doppler vibrometer (a) schematic; the vibrating object at right provides reflection of the laser light on the measurement path, while the fixed mirror on the top is a part of the reference path. An AOM is used in the reference path to permit measurement of the objects vibration phase by shifting the reference lasers wavelength by a fixed amount (40 MHz in our system). The system misalignment is greatly exaggerated to clarify the propagation path of the laser. If the vibrating surface is transparent, the desired interface must be located within the focal plane, with other interfaces omitted; see Fig. 1(b) in Ref. 21, for example.

the edges of the droplet given the strong curvature of the interface. The edges of the droplet will also tend to vibrate in directions not detected by the LDV, i.e., almost perpendicular to the measurement path.[27] Finally, near the edges of the droplet, the depth of field may encompass both the substrate and the fluid surface, amalgamating the vibration of both surfaces together in a way that obscures the true motion of both surfaces. If the fluid used is transparent at the wavelength of the laser, these problems are especially troublesome. Using dye in the fluid is an effective solution to the measurement problem, and was used in Figs. 1(d) and 1(e) to ensure the measurement was of the actual interface to the edges of the fluid droplet.

With this method, fast Fourier transforms may be used to determine the frequency spectral content of the vibration, which was instrumental in finding that the capillary waves generated on the surface of a fluid drop by SAW excitation at a frequency of f were *not* appearing at $f/2$ according to the theory associated with Faraday waves,[1,4,7–9,28,29] helping us to explain[14] why aerosol mists formed by high-frequency ultrasonic excitation of fluids had droplet diameters far different than predicted by the Faraday wave theory.[16] Further, the approach helped us explain very peculiar colloidal concentration phenomena[21] driven in part by capillary waves.

III. METHOD

Precision interferometry was one of the first uses of lasers, from soon after their invention in the late 1950s.[30] As a monofrequency coherent light source, they were ideal for the purpose and far superior[31] to prior approaches used to measure the “luminiferous ether”[32] to the extent that they now are even routinely used to characterize the motion of microelectromechanical structures.[33] Combining microscopy and more recent advances in optical technology, it is now possible to use interferometry to scan surfaces of vibrating objects. If the motion is harmonic, the amplitude and phase of each point’s motion can be measured with respect to some signal driving the motion. For example, in piezoelectrically driven oscillation, the voltage signal for the electric input to the piezoelectric element may be used as the reference, and so the phase between different measurement points may be compared. The surface must be reflective to provide an adequate specular return signal to complete the measurement leg of the interferometer; this is distinctly different than the requirement of laser *transmission* in the laser Doppler anemometry.[34]

Laser Doppler vibrometers work by interfering the reference laser light with the measurement laser light using the arrangement depicted in Fig. 2. A beating pattern is formed,

$$\sin 2\pi f t + \sin 2\pi (f+\Delta f)t = 2\cos \Delta\pi f t \sin(2f+\Delta f)\pi t, \tag{1}$$

where f is the original frequency of the laser radiation, Δf is the frequency shift due to the Doppler effect of the laser reflected off of the vibrating object, and t is time. Filtering out the high-frequency $2f+\Delta f$ signal provided by the photodiode and using only the beat signal Δf, one can determine the velocity of the object from the well-known Doppler equation $f+\Delta f = fc/(c+v)$, where c is the speed of light in the medium (air in our case) and v is the velocity of the object's motion. This v is the vibration velocity of the surface and is not associated with the velocity of the acoustic wave in the object, i.e., the wave velocity of the SAW (approximately 3588 m/s in our device). The acousto-optic modulator (AOM) (or Bragg cell) on the reference path shifts the frequency of the reference laser light by a fixed amount, 40 MHz in our system, so that one can determine the vibration phase.

Our system (MSV-400 Microscope Scanning Vibrometer, Polytec, Waldbrunn, Germany) offers the ability to scan across a defined mesh of points on a surface at about 2.5 kHz, and with the software provided, determines and corrects the time delay in measurements as the scan progresses to provide a consistent representation of the vibration across the scanned region. The system is capable of measuring vibration velocities from a few nm/s to 10 m/s from dc to 40 MHz in frequency, and, through use of the phase of the measured beat signal, provides displacement data with a resolution of 20 fm to amplitudes of 10 mm.

The general method is as follows (also see Fig. 1):

Sample preparation. The laser radiation must be reflected from a measurement surface with sufficient intensity back along the measurement path to provide an interference signal at the photodiode. Therefore, the interface to be measured must have a flat surface appropriate for delivering a specular reflection of the incoming laser back to the laser Doppler vibrometer. Higher quality vibrometers are able to automatically adjust the intensity of the incident laser light to permit measurement of oblique specular surfaces.

Focal plane verification. To avoid measuring the wrong vibrating surface—our substrate surface rather than the droplet surface, for example—the location of the focal plane must be confirmed through measurements against the objective lens specifications or simply by first defocusing such that the focal plane is above the fluid surface and then adjusting the focus to bring the focal plane onto the free fluid surface. Opaque dyes may solve this problem for many cases.

One must also ensure that the depth of field is short enough to capture only the interface. Since our MSV-400 has a laser that is passed through lenses along the measurement path, it has a specific and controllable focal length and a fixed depth of field depending on the objective lens (refer to Fig. 2). The depth of field in the configuration used for this study was 200 μm. While the effects of depth of field on imaging is well known, the effect on the laser Doppler velocimetry with the optics in the measurement path is to simply restrict the measurement volume to be a cylinder defined by the focused diameter of the laser and the depth of field. Laser radiation reflected back toward the LDV from surfaces outside the depth of field is defocused at the photodiode and has little interference with the laser propagating along the reference path. One must take care to ensure that the depth of field is larger than the magnitude of vibration of either the free surface of the fluid or the substrate so the effects of the vibration will not move the surface out of the depth of field.

Vibration measurement. This is essentially elementary with the use of modern LDVs although one must exercise due care to confirm that the surface remains within the focal range of the LDV's objective lens. Scanning laser Doppler vibrometers offer phase-corrected measurement of many hundreds of adjacent points; one must ensure that the point density is sufficient to capture the shortest wavelengths of the capillary wave per the standard Nyquist–Shannon criterion.[35]

A further concern in measurement is the effect of compressibility on the index of refraction. As the laser travels along the measurement path, it can be affected by temporal changes in the index of refraction, and this can even be used as a method for measuring fluid flow.[36] If the index of refraction remains fixed along a majority of the path over the time of measurement, however, the sole contribution to the Doppler shift is the motion of the object being measured.

Data processing. Given the complexity of typical capillary waves with responses across a broad range of wavelengths, the frequency domain representation is far more informative than a spatial domain representation, and can help directly indicate the nature of the capillary wave itself.[25]

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