Experimental Thermal and Fluid Science 71 (2016) 52–56

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Capillary waves in a sharp-edged slit driven by vertical vibration

Young Kwon Kim [1], Jiwoo Hong [1], Kwan Hyoung Kang, Sang Joon Lee *, Joonwon Kim *

Department of Mechanical Engineering, Pohang University of Science and Technology, San 31, Hyoja-dong, Pohang 790-784, South Korea

ARTICLE INFO

Article history:
Received 16 March 2015
Received in revised form 21 August 2015
Accepted 10 October 2015
Available online 23 October 2015

Keyword:
Open microfluidics
Meniscus oscillation dynamics
Capillary wave
Faraday wave
Subharmonics

ABSTRACT

We report an experimental study on capillary waves in a sharp-edged slit driven by vertical vibration. The standing waves of pinned meniscus oscillation in the transverse direction are determined by an applied frequency related to a dispersion relation. Standing wave patterns with mode numbers of up to 5/2 can be observed. The meniscus oscillation between the pinned edges exhibits a subharmonic mode above the critical acceleration (force), which tends to increase with increasing mode number (frequency). A subharmonic mode appears when a longitudinal wave is generated.

1. Introduction

Meniscus oscillation dynamics with pinned contact line is one of the silent processes in various practical applications, such as liquid lenses [1–4] and inkjet printing systems [5,6]. Liquid lenses with pinned contact lines are capable of aligning the optical axis with the center [1,2], preventing energy dissipation associated with moving contact lines [3,7], removing contact angle hysteresis, and avoiding the entrainment of the surrounding medium [1,8]. Liquid lenses are also more suitable for achieving high-speed responses under pressure-driven actuations than interfaces with free contact lines [2,4,9]. Despite these characteristics, liquid lenses exhibit minor problems, such as spherical and chromatic aberrations. Thus, a solid understanding of pinned meniscus oscillation dynamics is important for overcoming throughput.

Printing systems are another representative application that exhibits pinned meniscus vibration after droplet ejection. Given that printing devices should be capable of forming fast and stable drops in equal volumes for high productivity, the meniscus must be rapidly damped for subsequent drops to be dispensed. However, satellite drops are formed with the increasing dispensing frequency of drops (firing frequency) because of meniscus instability, thus resulting in low printing quality [10,11]. When applied frequency exceeds 20 kHz, bubbles are sometimes trapped in the inkjet nozzle, thus decreasing operation performance [12–15]. A concrete understanding of pinned meniscus vibration dynamics is necessary to solve the instability of the meniscus after drops are dispensed and to improve printing quality.

Another important issue is subharmonic resonance, which induces the half-motion of a meniscus compared with an applied frequency. Given that the meniscus slowly oscillates with half the applied frequency, subharmonic resonance is an important challenge in improving the response time and shape control of the meniscus. Subharmonic motion was first reported by Faraday [16], who found that when a basin with water was vertically vibrated, the water surface with free contact line oscillated with subharmonic motion. Several studies have been conducted on free contact line conditions from small droplets to thick fluid layers. Benjamin and Ursell derived the natural frequency of a surface from the dispersion relation of free contact line [17]. Kumar and Tuckerman determined that critical acceleration is important for subharmonic motion because of the effects of viscous dissipation around the wall [18]. However, only a few studies on pinned meniscus oscillation have been conducted. Benjamin and Scott [19] and Graham-Eagle [20] concluded that there is a subtle difference between natural frequencies of inviscid gravity-capillary waves with free and pinned contact lines. They also reported that the natural frequency with a pinned edge condition cannot be expressed in explicit form. However, these works are not about parametrically forced waves but free waves. And Miles and Henderson stated that, although the meniscus effects were ignored in many theoretical works, when the wavelength is sufficiently small ($\leqslant$1 mm) the free and pinned edge conditions of a meniscus dynamics are significant for the natural frequency and viscous dissipation [21]. As the field of open microfluidics including

* Corresponding authors. Tel.: +82 54 279 2169; fax: +82 54 279 3199 (S.J. Lee). Tel.: +82 54 279 2185; fax: +82 54 279 5074 (J. Kim).

E-mail addresses: sjlee@postech.ac.kr (S.J. Lee), joonwon@postech.ac.kr (J. Kim).

[1] These authors equally contributed to this work.

http://dx.doi.org/10.1016/j.expthermflusci.2015.10.011
0894-1777/

liquid–vapor or liquid–liquid meniscus interfaces has made significant progress [22–24], further systematic research on a capillary-dominant regime is required to clearly understand the pinned meniscus dynamics.

This study aims to simulate meniscus oscillation in practical applications, such as liquid lenses and inkjet systems. Capillary waves that are pinned at a sharp-edged slit without a wall effect and driven by vertically mechanical excitation are studied. The effects of frequency and acceleration on the characteristics of the capillary wave pinned at the edges are investigated. The change in wave patterns according to applied frequency is also observed. The transition from harmonic to subharmonic motion is found above certain accelerations at a fixed frequency that is obtained from measuring various frequencies.

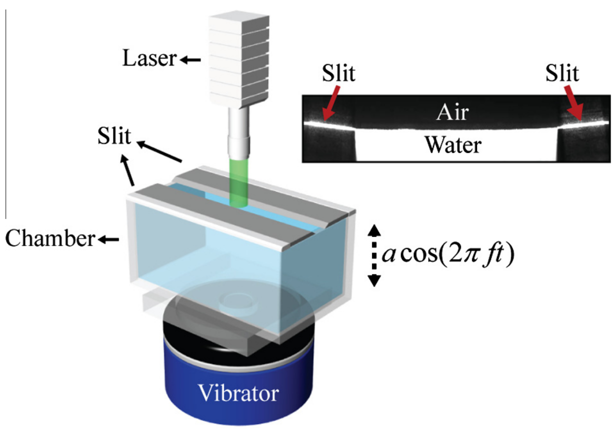

Fig. 1. Schematic diagram of the experimental setup. Inset figure illustrates meniscus between sharp-edged slits before applying mechanical vibration. Here, a and f denote the applied acceleration and frequency, respectively.

2. Materials and methods

Our experimental setup is similar to the conventional experimental apparatus for observing Faraday waves (Fig. 1) [25,26]. The experiments are performed in a transparent acrylic vessel that is 90 mm long, 40 mm wide, and 30 mm deep. Two parallel snap-off blades with a 5 mm gap are combined on the upper side of the vessel to eliminate any viscous dissipation effects around the sidewall. The vessel is filled with deionized water up to the keen edges of the blades. The deionized water acts as the pinned ends (Fig. 1). A vibrator (SSP 4.0 Transducer, Revolution Acoustics™) is attached to the bottom of a transparent acrylic vessel to apply vertically mechanical vibration to the vessel. The vibrator is driven by an amplifier (EP4000, Behringer) and a function generator (33220A, Agilent) to change the frequency (30–650 Hz) and the amplitude of the sinusoidal signal. An accelerometer (P3SCM, Rectuson) is connected between the vibrator and the vessel. The signal acquired from the accelerometer represents the acceleration of the vessel and follows the input signal from the vibrator. To visualize the movement of the meniscus between the two blades, we add a dye (Rhodamine B, Sigma–Aldrich) to the water solution. The surface tension of the aqueous solution with the dye is measured at 66.73 ± 0.05 mN/m by using a Du Noüy ring tensiometer (Lauda TD2). The meniscus between the two blades is illuminated by a sheet of laser beam that is generated by a Nd:Yag laser (532 nm wavelength, VA-III-N-532, Viasho). The laser sheet is 0.2 mm thick.

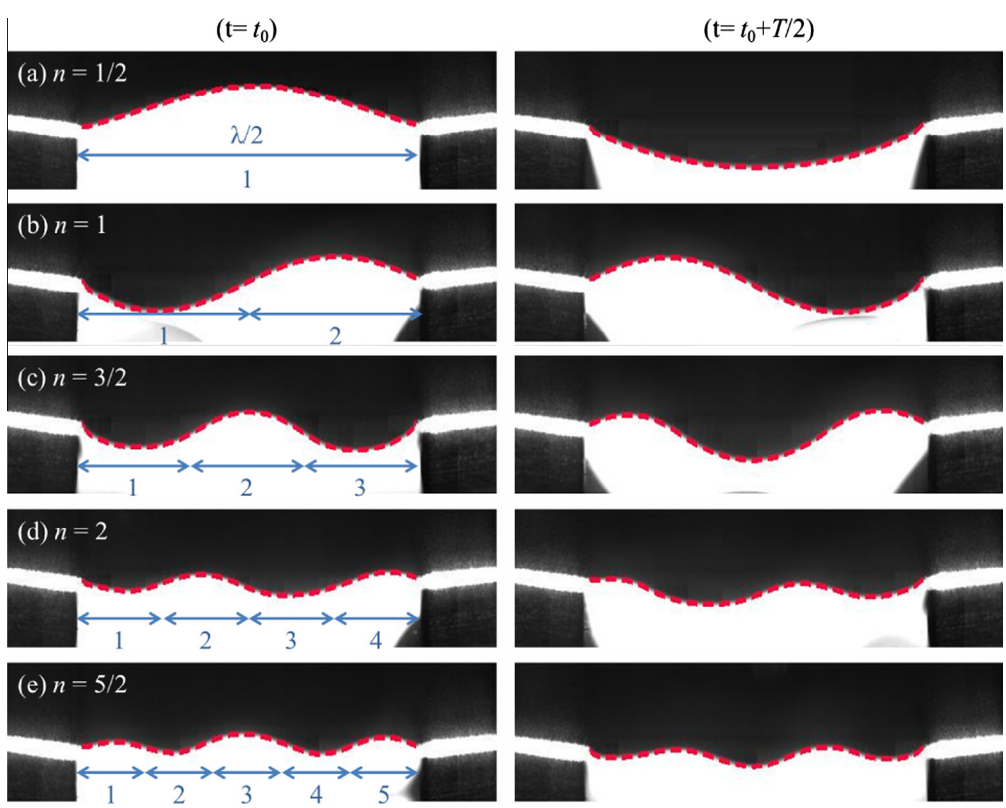

Fig. 2. Patterns of the capillary wave with the mode number n in a transversally cross-sectional view; (a) $n = 1/2$, $f_a = 60$ Hz, (b) $n = 1$, $f_a = 123$ Hz, (c) $n = 3/2$, $f_a = 174$ Hz, (d) $n = 2$, $f_a = 281$ Hz, (e) $n = 5/2$, $f_a = 315$ Hz. Left images are recorded after half period $T/2$ of each mode. Here, λ denotes wavelength. The blue arrows and red dashed line represent the number of half wavelengths for each mode and surface profile, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)