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Experimental investigation on the atomization of a spherical droplet induced by Faraday instability

Fushui Liu[a,b], Ning Kang[a], Yikai Li[a,*], Qing Wu[a]

[a] School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China
[b] Beijing Electric Vehicle Collaborative Innovation Center, Beijing 100081, China

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ABSTRACT

Faraday instability plays an important role to realize liquid atomization which has been widely applied in various fields. The spherical Faraday instability has different characteristics from the planar one. It is of great importance to understand the fundamental mechanisms of the surface deformation evolution and atomization of a spherical droplet induced by Faraday instability. In this paper, we first experimentally recorded the deformation and fragmentation process of a spherical droplet on a vertically vibrated plate with high speed camera. The results showed that the zonal, meridional and approximately circular standing waves in proper order exist on the surface of the spherical droplet with the increase of excitation amplitude. When $Bo < 3.0$, the modes of low (zonal) and high (meridional) order m of the spherical harmonic occur more easily, and as Bo is increased, the order m becomes closer to the intermediate value of spherical mode number l. The mechanism of droplet atomization is that a spike forms first on the droplet surface due to the impingement of the liquid flowing from the neighboring trough portions, and then a neck appears because of the velocity difference between the head and bottom of the spike, and the velocity difference determines whether the head liquid can form a sub-droplet ejected from the surface of the parent droplet. The Mathieu equation was derived by a linear theoretical analysis with inviscid and incompressible assumptions for the spherical Faraday instability, in which the parameters have different definitions from its planar counterpart. In the instability diagram, the iso-curves of larger linear growth rate deviate further from the ordinate axis and finally disappear. It is also validated that Lang's equation is applicable to the spherical Faraday instability in low frequency.

1. Introduction

liquid atomization plays a significant role in many industrial fields, which can be realized by various techniques. One universal method is exerting a vertical vibration on a body of liquid to produce small droplets from its surface, such as the ultrasonic atomization [1], surface acoustic wave (SAW) [2,3], and so forth.

When the excitation amplitude is small, standing waves are always observed on the horizontal liquid surface. This phenomenon was first observed by Faraday [4], who found that the oscillation frequency of the standing waves equals half of the excitation frequency. Since then, Faraday instability has attracted much research attention. In the linear regime for ideal fluids, Benjamin and Ursell [5] theoretically analyzed the planar Faraday instability and derived a standard Mathieu equation to govern the amplitude of the liquid surface deformation. According to their theory, surface deformation with sub-harmonic, harmonic, or higher-order oscillations is excitable when the oscillation frequency is equal to n/2 times the excitation frequency, where n = 1, 2, 3, … . Later, Eisenmenger [6] simply added a linear damping term to the Mathieu equation to emulate the viscous effect. Kumar and Tuckerman [7,8] accurately studied the effect of viscosity on planar Faraday instability by a Floquet analysis starting from the linearized Navier-Stokes (NS) equations. They argued that the surface response observed by experiments is always sub-harmonic because the leftmost point of the sub-harmonic response moves least under the effect of viscosity.

When the surface deformation is large and comparable with the wavelength, nonlinear effects become dominant. One striking nonlinear behavior due to planar Faraday instability is the formation of the surface standing wave patterns [9]. Chen and Vinals [10] theoretically studied the dependence of the patterns on the excitation frequency and fluid properties, and their findings were validated by subsequent experimental investigation conducted by Westra et al. [11] in the excitation frequency range of 20–45 Hz. Perinet et al. [12] 3D numerically studied the dynamics of Faraday patterns for two immiscible and

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[*] Corresponding author.
E-mail address: liyikai@bit.edu.cn (Y. Li).

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immiscible viscous fluids and successfully simulated the square and hexagonal surface patterns, which agreed well with Kityk's experiments [13].

When the excitation amplitude is sufficiently large, small droplets can be ejected from the planar surface, which is usually applied for liquid atomization. One typical technique is the so-called "ultrasonic atomization", the excitation frequency of which is on the order of 10 kHz–1 MHz. Lang [1] first experimentally researched the ultrasonic atomization in the frequency range of 10–800 kHz and found that the mean droplet diameter could be described by $d_m = 0.34b$, where b is the wavelength of the surface waves. Following Lang's work, lots of studies on ultrasonic atomization have validated Lang's results and numerous methods to provide a theoretical explanation have been made, seen in literatures [14–19]. Besides, there also have been some studies [20–22] on liquid atomization of planar surface at relatively low excitation frequencies (< 1 kHz).

Faraday instability on the non-planar liquid surface is also interesting for researchers. Kelvin [23] and Rayleigh [24] considered the problem that an inviscid spherical droplet that is slightly disturbed, and derived an expression for the free oscillation frequency of the droplet. Okada [25] experimentally investigated the various behaviors of a water droplet placed on an oscillating horizontal plate within a frequency range of 10–700 Hz. Brunet and Snoeijer [26] produced an air cushion by the air stream flows through a porous substrate below to levitate the water droplet and observed the oscillation patterns of the droplet for different air flow rates. Shen et al. [27] studied the oscillation characteristics of a levitated water droplet, on which sectorial acoustic forces were applied, and proposed a modified Rayleigh equation to describe the dependence of the droplet oscillation frequency on the drop size and oscillation mode. James et al. [28,29] and Vukasinovic et al. [30,31] placed a droplet on a vertically vibrating diaphragm to realize atomization, which is called the vibration-induced drop atomization (VIDA), and obtained the threshold of the excitation acceleration for generating sub-droplets. In addition, Qi et al. [2] and Tan et al. [3] conducted a fresh scenario that they made the surface acoustic waves travel through a liquid droplet which was placed on a piezoelectric substrate, and studied the mechanism of this kind of droplet atomization.

From the previous studies we can see that there has been a lot of fruits associated with the Faraday instability obtained, such as the dispersion relation of the wave number and linear growth rate, the thresholds of different wave patterns and the size of atomized sub-droplets. However, the studies on the atomization of a spherical droplet induced by Faraday instability are still lacking. To understand the fundamental mechanism of the atomization of a spherical droplet on a vertically vibrating plate, we must first obtain the detailed micro-dynamics of the atomization process and conduct the theoretical analysis for spherical Faraday instability to study the unstable nature and the most-unstable mode for a specified condition, which would provide deep physical insights into the spherical Faraday instability. To the best of our knowledge, there are very few researches focusing on these issues. Thus, in the present paper, we explore the deformation and fragmentation process of a droplet induced by Faraday instability in more detail with a high-speed camera. The effects of the excitation amplitude on the droplet evolution process and the size of atomized sub-droplet and the mechanism of droplet atomization are further investigated. With the incompressible and inviscid assumption, we then conduct a linear theoretical analysis of the spherical Faraday instability. Similar to the planar case, a Mathieu-type equation is derived with different definitions of the parameters. Finally, the relationship between the excitation amplitude, the spherical mode number and the maximum linear growth rate are discussed along with the experimental results.

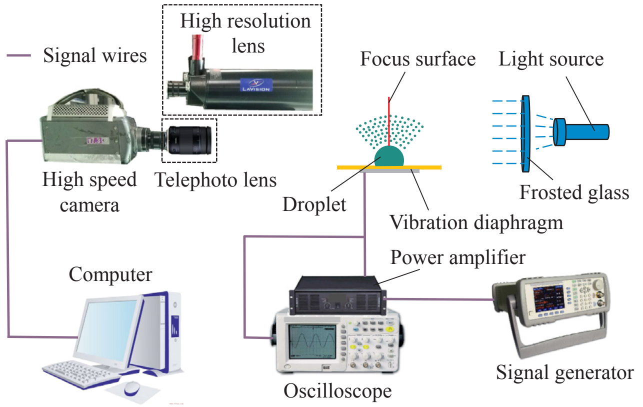

Fig. 1. Schematic diagram of the experimental system.

2. Experimental setup and method

The schematic diagram of the experimental system for this work is shown in Fig. 1. The similar experimental method with James [29] was adopted to vibrate the liquid droplet. The experimental principle is to utilize the piezoelectric properties of the piezoelectric ceramic which can expand and compress under the variable voltage. The metal disk was a circular copper-zinc slice 35 mm in diameter and 0.1 mm thickness. The piezoelectric ceramic, which was PZT5 20 mm in diameter and 0.12 mm thickness, was centrally plated on the lower surface of the metal disk to create a vibration diaphragm. The diaphragm was excited by using a signal generator coupled with a power amplifier that applied a sinusoidal voltage to the piezoelectric ceramic, and this caused the diaphragm to vibrate in the vertical direction in the axisymmetric mode. In this work, the resonance characteristic was utilized to improve the vibration energy for droplet atomization. The acceleration amplitude of the diaphragm increases with the increase of the excitation voltage and is great large in the vicinity of its resonance frequency, which had been noted by James' experiment [28]. The frequency and voltage of the signal applied to the diaphragm could be modified flexibly by the signal generator and monitored by an oscilloscope.

A micro-pipette manufactured by DRAGONLAB was used to place an accurate volume droplet on the center of the upper surface of the diaphragm. The micro-pipette has a volume range of 20–200 μL and the maximum permissible systematic error of 1.2 μL. The placement of the droplet at the center of the diaphragm was accurate to about 0.5 mm.

To clearly record the deformation and atomization process of the droplet, a xenon lamp and a high-speed camera were used together to illuminate and capture the very fast droplet deformation and atomization process. The power of the light is 300 W. The camera is Phantom V7.3 and made by Vision Research, and respectively assembled two kinds of lens for different research purposes. A telephoto lens with a focal length of 180 mm was used to capture the dynamic and detail features during the droplet atomization process, such as the formation and production process of a single sub-droplet, and the camera was operated with a 5 μs shutter speed and a video-framing rate of 20 000fr/s. A high resolution lens, which can capture the displacement in μm rank, was used to measure the displacement of the vibrating diaphragm for quantitative study, and the camera was operated with a 3 μs shutter speed and a video-framing rate of 80,000fr/s, which is enough for our experiments.

In the experiments, we mainly focus on the deformation and fragment process of the distilled water droplet. The volume of the droplet was fixed at 200 μL and about 10 mm width in actual size. The frequency of the excitation signal was fixed at 1.35 kHz that is the resonance frequency of the vibrating diaphragm, and the peak-peak voltage of the sinusoidal signal varied within the range of 0–70 V. Fig. 2 displays the amplitudes of the acceleration of the diaphragm under