Observation and Analysis of Surface Acoustic Wave Induced Atomization

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Abstract: The ability to excite instabilities in free fluid surfaces via acoustic excitation is well known, even to the point of atomization. Surprisingly, atomization phenomena exist at frequencies up to 1 GHz, because peak piezoelectrically-driven vibration velocities remain remarkably constant at about 1 m/s regardless of the excitation frequency if one makes use of different materials and vibration modes along the way. At 100 MHz, for example, we have maintained surface acoustic waves 1 m/s vibration velocity and measured displacements and accelerations of 10 nanometers and 10 million m/s^2. At these extreme conditions, fluid microfilaments, multiscale droplet formation, and other curious phenomena appear. Understanding the behaviour is important for applications in rheology and the study of solid-fluid interactions on the micro and nanoscale, and we illustrate methods for observation of the atomization and vibration conduction processes under these conditions.

Keywords: surface acoustic waves, atomization, structure-fluid interaction, piezoelectricity, Rayleigh waves.

1 Introduction

Atomization of fluids at a fluid-fluid interface is a complex phenomenon studied since the late nineteenth century. Two distinct approaches have been used over the years, one in which the ejection of individual droplets occurs from an orifice, and the other with droplets appearing from a much larger interface due to an induced instability.

Acoustic atomization is especially common since high-output lead zirconium titanate (PZT) piezoelectric elements became commodity items in the late 1990s. From rather complex systems employing Langevin transducers to generate atomized droplets at low ultrasound, 20-40 kHz, to essentially single-PZT element thickness-mode atomizers operating at 2 MHz [i,ii], a variety of approaches to generate droplets are commercially available. The formation of droplets from capillary waves was first described by Rayleigh in 1883, as a *Rayleigh instability*, and later revised by Lang [iii] using atomization experiments performed up to 1 MHz. Lang found that a relationship between the atomized droplet diameter and the frequency of excitation could be defined as

$$D \sim \left(\frac{8\pi\gamma}{\rho f^2}\right)^{1/3}, \qquad (1)$$

where the surface tension, γ, and density of the fluid, ρ, also influence the droplet diameter. The atomization is presumed to occur into air, which has little effect on the droplet diameter. Since Lang's work in 1962, there have been many publications on atomization and estimates of droplet diameters based on different possible physical mechanisms from

A different approach is used here [iv], with far higher frequencies of excitation—5-500 MHz—via surface acoustic waves generated along a single-crystal piezoelectric substrate. As a rule, vibration generated via piezoelectric materials can induce a particle velocity of around 1 m/s as the wave passes regardless of the frequency. At 10 MHz and 1 m/s particle vibra-

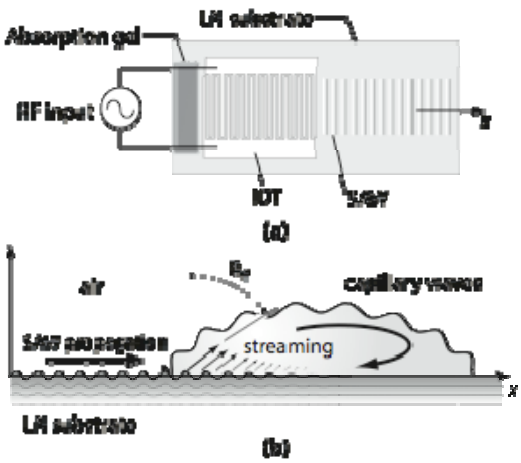

Fig 1. Schematic top view of (a) a SAW atomization device and (b) the interaction between the SAW and a fluid droplet atop the device.

tion velocity, the particle displacement is on the order of 10 nm, while the acceleration is 10 million m/s^2. Capillary waves easily appear upon a droplet that are subjected to this radiation, and indeed atomization occurs at quite low IDT input power. The SAW propagates across the substrate as a transverse-axial elliptical *Rayleigh* wave at 3965 m/s in LN, and as a compressional wave at 1485 m/s in water. The difference in wave speeds causes the compressional wave to propagate in the fluid at an angle $_R$ = 23° —the *Rayleigh angle.*

2 SAW Atomization of Fluids

Here the SAW atomization device is a single interdigital transducer (IDT) consisting of 25 pairs of straight electrodes formed of 250 nm aluminum atop a 4 nm titanium layer in a basic full-width interleave configuration sputter-deposited onto a 127.68°Y-X-cut lithium niobate ($LiNbO_3$ or LN, Roditi UK, Ltd., London) single crystal piezoelectric substrate, as schematically depicted in Fig. 1(a). Surface acoustic waves are generated across the LN substrate via an sinusoidal electrical input into the interdigital electrode. Acoustic streaming and subharmonic capillary wave generation occurs in a fluid droplet placed on the substrate as a consequence of interaction with the SAW. The acoustic streaming induces internal recirculation while the oscillatory acoustic field induces the capillary waves.

Absorption gel (α-gel, Geltec Ltd., Yokohama, Japan) was used to suppress the leftward SAW from the IDT. The SAW wavelength λ was chosen to be 100 μm, thus specifying the electrode and interelectrode gaps along the *x*-axis at 25 μm. The IDT finger width perpendicular to the *x*-axis is 10 mm with a gap of 1 mm between the electrode ends and opposite bus bar, which has a width of 3 mm. Application of an oscillating electric field matching the designed resonance frequency of 20 MHz at a power of 3 W then induces a shallow (3-4 λ deep) electroelastic Rayleigh wave [v] along the substrate surface with a displacement of approximately 10 nm, as illustrated in Fig. 1(b), sufficient to atomize water, ethanol, or acetone. Observation of the atomization was performed using a 10 μℓ droplet of water viewed with a 32,000 fps CCD Olympus iSpeed camera coupled to an Infinivar 150x zoom lens. The field of view was restricted to the air-water interface.

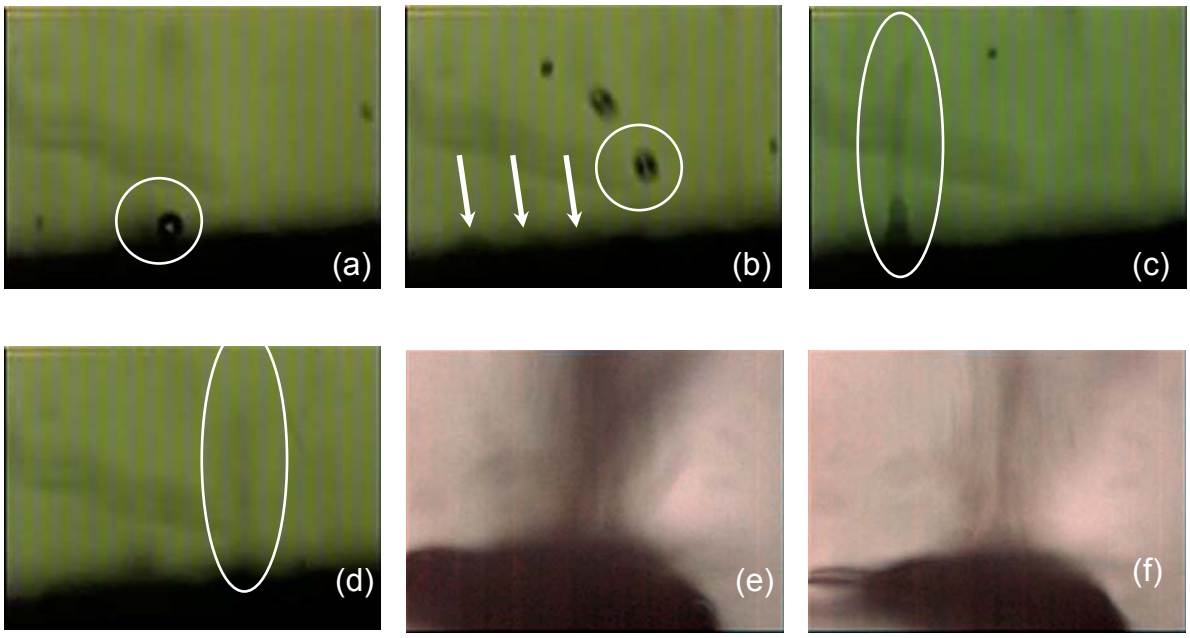

Fig 2. Stills taken from 10 000 fps video of the atomization of water atop a 20MHz SAW device; each frame is 100 μm wide. During atomization, (a) 5-10 μm droplets appear and are predicted by eqn. (1) from the capillary-wave Rayleigh instability. Some droplets (b) are ejected at speeds of up to 1 m/s; note the capillary wave is also visible (arrows), and (c) jetting is apparent as well, which is not explained by the Rayleigh instability. Such jets breakup into a submicron mist possibly due to the Kelvin-Hemholtz instability or simply bag breakup in a process that remains unclear. Reducing the size of the droplet further makes the submicron mist (e-f) more apparent in the video frames; here the mist appears directly from the fluid drop surface.

Frames of the atomization are shown in Fig. 2. While droplets do appear that are of a size predicted by the Rayleigh equation, eqn. (1), high-speed jetting and submicron mist appear that are not explained by the research literature with the exception of discussion of mist appearing in photos by Barreras, et al. [vi]; they hypothesized the submicron mist occurs from cavitation at the surface, an idea propsed by Mir in 1980 but never verified [vii]. Curiously, Holland and Apfel [viii] suggest a means to determine whether cavitation is responsible or not by degassing the fluid. Given the fact the capillary wave formation via the Faraday resonance is exceptionally nonlinear [ix], with subharmonic and superharmonic waves appearing from very narrowband SAW excitation at 20 MHz, the former as low as 100 Hz [x], it is conceivable the atomization is still occurring from capillary waves occurring at different wavelengths, and that the submicron mist is appearing from superharmonic capillary wave atomization rather than cavitation. A comparison of the atomization results using degassed water is underway, as is the use of a 40 MHz scanning laser Doppler vibrometer (MSA-400, Polytec PI, Waldbrunn Germany) to perform vibration spectroscopy of the fluid droplet surface as atomization is initiated. This will suggest whether cavitation or multi-wavelength capillary waves are responsible for the submicron droplets. A third possibility, albeit unlikely, is that the droplets being ejected are breaking up post-ejection [xi]. It is unlikely because the Weber number is far too low to allow for such breakup events in this configuration. Finally, the jetting occurring from the surface is known to break up due to shear from the high speed of the jets in a Kelvin-Helmholtz instability [xii], but the resulting droplets are known to be of a size comparable to the diameter of the jet, 2-5 μm for this configuration.

3 Conclusions and recommendations

Acoustic atomization of fluids at very high frequencies has been illustrated using surface acoustic wave devices, and the physical process of droplet formation using this technique shows droplet formation that is significantly different than atomization phenomena seen at lower frequencies. In particular, the appearance of submicron droplets is not explained by the Faraday generation of capillary waves and resulting Rayleigh instability. Most likely these droplets are appearing as a consequence of cavitation or capillary waves appearing from superharmonic excitation, which will be determined in the next few months by the use of laser Doppler vibration spectroscopy and the control of dissolved gases in the fluid.

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