tip, which can induce structural surface and subsurface modifications at highly oriented pyrolytic graphite and thus facilitate the patterning of nanoscale surface features [7].

There are variations on the basic USM techniques. Rotary ultrasonic machining (RUM) [8, 9] is the technique involving the vibration of a small grinding toll, which is excited and simultaneously rotated. The technique permits increase in machining speed and decrease in machining forces, a useful condition for machining with fragile tools. The same advantages of smaller forces can be obtained by applying ultrasonic vibrations to a surgical tool in various medical applications. Examples include ultrasonic assistance dental cutting, brain tumor removal, and artery surgeries [9, 10].

Cross-References

▶ Biosensors Using Atomic Force Microscopes
▶ Bulk Micromachining
▶ Integrated Microdevices for Biological Applications
▶ Microturbines
▶ Particle Manipulation Using Ultrasonic Fields

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Ultrasonic Pumps

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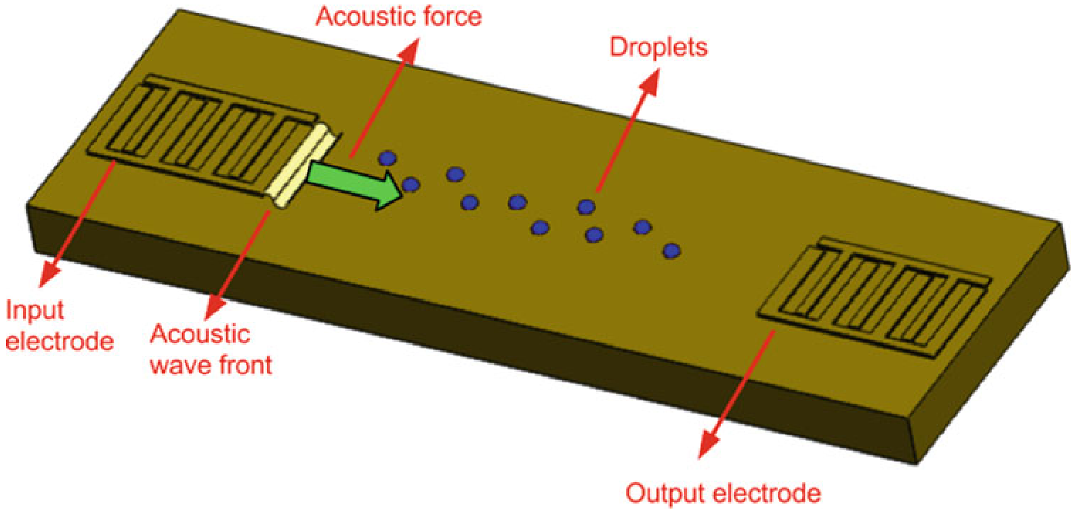
Synonyms

Acoustic pumps; Acoustic streaming pumps

Definition

Ultrasonic pumps are the pumps that use acoustic streaming effect to create fluid flow. The acoustic streaming effect arises from the interaction between the surface acoustic waves (SAW) traveling inside a piezoelectric substrate and the fluid. Attenuation of the SAW traveling inside the fluid (via reflection, diffraction, etc.) generates a body force within the fluid which is in the direction of wave propagation and converts acoustic energy into kinetic energy of the fluid [1]. SAW devices can be used to transport droplets on a free surface between the input and output piezoelectric transducers (also known as interdigital transducer (IDT)). A schematic drawing of such a device is given in Fig. 1. Moreover, the same mechanism can be used to drive droplets as well as bulk fluid inside closed microchannels.



Ultrasonic Pumps, Fig. 1 Schematic drawing of a typical SAW device used for driving droplets on a free surface

Overview

Acoustic pumping has clear advantages in micropumping due to compactness, high precision, robustness, ease of control, valveless design, and ease of fabrication [2, 3]. Moreover, acoustic pumps have an extremely high frequency response (compared to mechanical pumps) which makes them ideal for control of time-dependent flows [4]. Unlike electroosmotic pumps, acoustic pumps are not sensitive to chemical and/or electrical properties of the fluid or the wall material. By using acoustic streaming as a pumping mechanism, noncontact fluid control is achievable, since SAW travel between the acoustic source and the fluid without any direct contact [5].

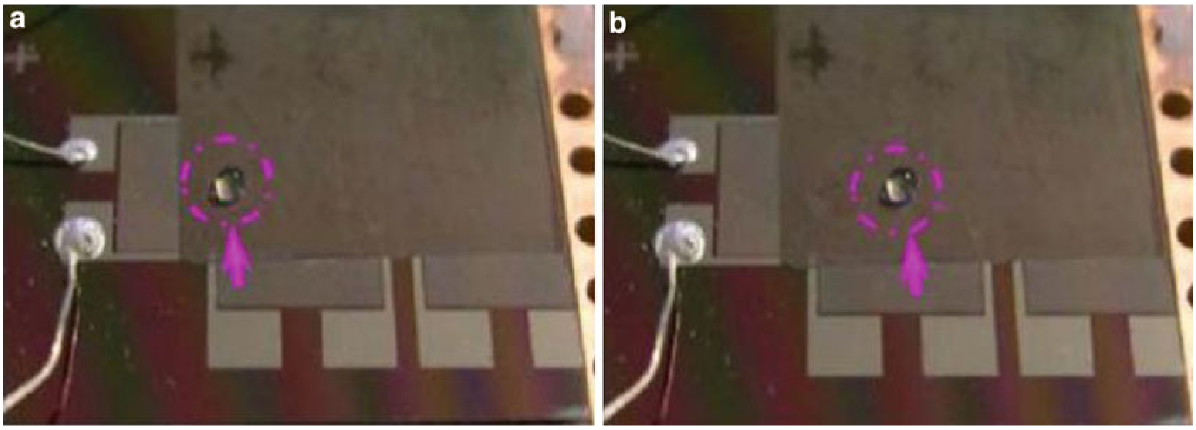
Basic Methodology

Acoustic streaming flow fields depend on acoustic wave properties, fluid properties, the geometry of solid boundaries, and presence of solid particles within the fluid. Depending on these factors, laminar, transitional, or turbulent flow with jets and vortices can be generated. The acoustic streaming effect is proportional to the sound pressure level and the square of the frequency of the pressure wave [1]. However, excessive heating (since most of the acoustic energy dissipates into heat) and bubble formation set the upper limit for high intensities [5].

An ultrasonic transducer is an integrated component of acoustic pumps. The transducers that generate ultrasonic energy with megahertz frequency for ultrasonic pumps make use of the piezoelectric effect. A piezoelectric layer is the vital component of the ultrasonic transducer and provides the oscillatory motion that ultimately produces the surface acoustic waves (a good review on IDT and SAW can be found elsewhere [3]).

Key Research Findings

Rifle et al. [6] developed a fluidic pumping circuit powered by an acoustic frequency of 50 MHz and generated fluid flow with velocities in the order of mm/s. They used ultrasonic piezoelectric transducers for their pump to generate the acoustic waves. The intensity of the waves was low enough to produce negligible heating; however, even if the heating can be tolerated, dielectric breakdown in the piezoelectric thin film limited their maximum intensity. These authors also discussed the bubble formation and concluded that for frequencies above a few MHz, it was safe to use degassed liquids without any cavitation problem.



Ultrasonic Pumps, Fig. 2 A 1 μl droplet on a ZnO SAW device before (**a**) and after (**b**) being driven by a RF frequency (Reprinted from Ref. [9] with the permission from Dr. Milne and Journal of Applied Physics)

Nguyen and White [7] presented a numerical study of the flexural plate wave (FPW) micropump. Their simulated device consisted of a channel with a thin piezoelectric membrane, whose thickness was 1–3 μm, attached to a bottom wall. This membrane generated the high-intensity acoustic field in the vicinity of the fluid inducing the motion of a fast-moving layer near the membrane. They investigated the pumping performance with different parameters such as the wave amplitude, channel height, and back pressure. They concluded that micropumps with a height of a few microns had a good performance due to their high flow rate and high hydraulic impedance against back pressure.

Du et al. [8] designed and fabricated a micropump using a 128° Y-cut $LiNbO_3$ layer with a thickness of 500 μm as the piezoelectric substrate. They demonstrated that their device was capable of driving droplets on a free surface as well as bulk fluid inside a microchannel. By changing the frequency of the SAW, they were also able to induce mixing inside the bulk flow which is a very challenging task in microfluidic devices due to the low Reynolds number nature of the flow. Flow velocities up to 1.4 cm/s for the droplets were reported. These velocities are at least an order of magnitude larger than those achievable via mechanical means. In another study [9], the same group fabricated an ultrasonic pump using a ZnO thin film on a Si substrate as the piezoelectric layer and reported droplet pumping with a velocity of 1 cm/s. Figure 2 shows the device in operation. More recently, Yeo and Friend [10] applied similar concepts and fabricated a SAW-driven droplet transport pump achieving velocities on the order of cm/s verifying that ultrafast pumping is achievable using ultrasonic pumps.

Schmid et al. [4] reported a closed-loop microfluidic network with integrated acoustic micropump. The pump consists of gold electrode IDTs on a 128° Y-cut LiNbO3 piezoelectric substrate fabricated by soft photolithography method. The reported flow rate was 0.15 ml/min at a back pressure of 4.8 Pa. They also simulated a 60 beat/s biofluid pumping which demonstrates the fast response time of the system. In this design, the pump was fully integrated on a chip with no external tubing which eliminates the contamination risk for bio-samples.

Hasegawa et al. [11] designed a bending disk driven by a ring-shaped PZT element bonded on the back of the disk with the vibrator disk being softly supported by a frame. With this configuration, they achieved a maximum flow rate of 22.5 ml/min against a back pressure of 20.6 kPa. The shape of the transducer was optimized to give the highest acoustic intensity.

Chao et al. [12] reported an ultrasound-actuated micropump which uses nonporous one-way membranes. The device consists of a PMMA pumping chamber with nanonozzles and diffusers. If the device is submerged in ultrasonic bath, it starts pumping the fluid. A flow rate of 0.603 μL/s against a back pressure of 200 mm H_2O was reported.

Future Research Directions

Acoustic waves can potentially damage biological samples (e.g., cause cell lysis). Due to this reason, careful control of the SAW frequency and device optimization are necessary. Understanding the complicated mechanisms governing the fluid–structure interactions will help in the optimization of ultrasonic pumps dealing with biological samples.

The hydrodynamics of the three-dimensional acoustic-driven droplet flows are to be investigated in more detail. Much has been done in modeling and designing acoustic devices capable of driving droplets on a free surface; however, much less effort has been put into development of their microchannel counterparts [10].

Cross-References

► Magnetic Pumps
► Piezoelectric Valves
► Thermocapillary Pumping

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Unbalanced AC field

Synonyms

Aperiodic AC field

Definition

A periodic alternating-current (AC) electric field is called unbalanced if its first moment has zero time average ($\langle E \rangle = 0$), but at least one of its higher moments does not (e.g., $\langle E^3 \rangle \neq 0$).

Cross-References

► Aperiodic Electrophoresis
► Electrokinetic Motion of Polarizable Particles
► Nonlinear Electrokinetic Phenomena