Characterization of Surface Acoustic Waves Diffraction Driven Mechanisms in Microfluidic Systems

Armaghan Fakhfouri[1], Citsabehsan Devendran[2], David J. Collins[3], Andreas Winkler[1], Hagen Schmidt[1], and Adrian Neild[2]

[1] *SAWLab Saxony, Leibniz IFW Dresden, 01069 Dresden, Germany, E-Mail: a.fakhfouri@ifw-dresden.de*
[2] *Department of Mechanical and Aerospace Engineering, Monash University, Clayton 3800, Victoria, Australia*
[3] *Department of Biomedical Engineering, University of Melbourne, Parkville 3052, Victoria, Australia*

Introduction

Acoustic forces arising from high-frequency surface acoustic waves (SAWs) underpin a broad range of promising techniques for a versatile, yet contactless manipulation of particles and cells in microfluidic systems. The acoustic effects exploited for manipulation, typically include acoustic radiation and acoustic streaming force fields that are often assumed to result from wave propagation in a simple planar fashion. However, the finite realm of a microsystem substantially increases the significance of diffraction, causing a far richer range of physical effects. This work aims to seek an in-depth understanding of the mechanisms arising due to the incidence of a travelling SAW (TSAW), emanating from a finite-width set of interdigitated transducers (IDT), in a microfluidic channel. Whilst the current literature broadly reports continuous unidirectional migration of particles along the TSAW propagation direction [1], here we show that this effect is only one amongst many. Through numerical prediction and experimental validation, five distinct acoustofluidic mechanisms have been identified and characterized.

Characterization of traveling SAW driven mechanisms

Here, a finite-width IDT with a wavelength of 21µm (operating at 180 MHz) is employed to generate TSAW. Upon interaction of 1 µm polystyrene particles with the generated TSAW field, five distinct mechanisms are observed (Fig. 1) [2]. In particular, a scenario is realized wherein trapping of particles into stable locations (in two orthogonal directions) occurs, though the periodic nature of this outcome is typically only expected for standing SAW systems. The periodic trapping of particles parallel to the propagation direction in a TSAW system (parallel trapping), is arisen by the diffractive effects at the wafer/liquid intersection. This phenomenon is predicted by simulations using finite element analysis (FEA) of a cross-section through the channel, indicating the complexity of the resultant time-averaged absolute pressure field (Fig. 1b). The trapping of particles orthogonal to the SAW propagation direction (orthogonal trapping), however, is caused by the diffractive patterns on the substrate surface due to the finite width of the incident SAW. Additionally, an acoustic streaming field is developed in the irradiated fluid that gives rise to fluid swirling in two orthogonal planes; lateral vortices at the peripheral regions of the SAW beam, here termed peripheral streaming (Fig. 1a), and vertical vortices within the extent of the SAW beam, here termed lobe streaming (Fig. 1a, Fig. 1c). Finally, unidirectional translation of particles along the SAW-propagation direction, the most reported effect in such systems. The dominance of these mechanisms, however, depends on the particles' size and their spatial location within the microfluidic channel.

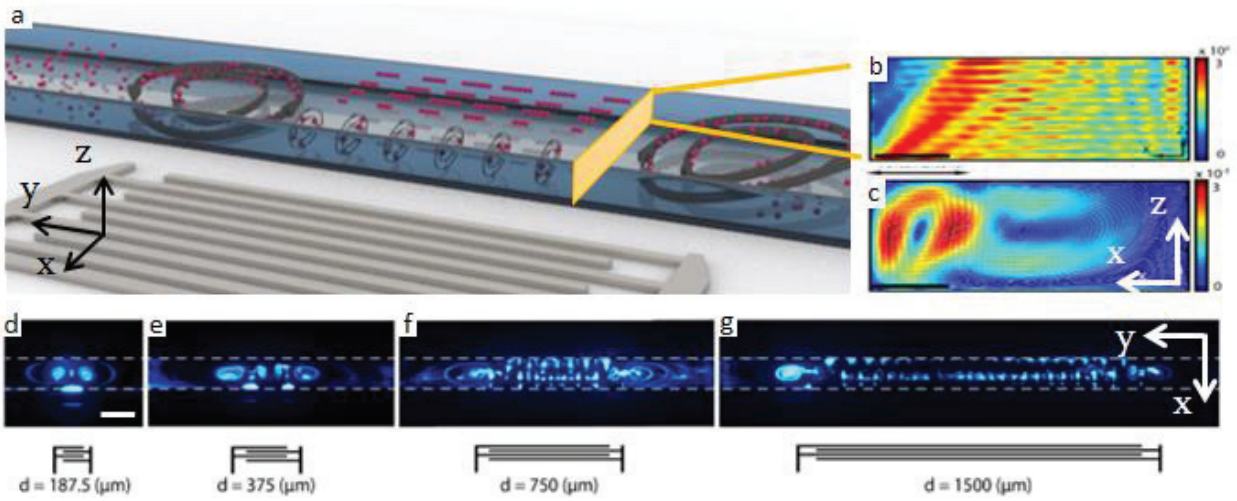

Figure 1: (a) Conceptual illustration of SAW-driven mechanisms (b) time-averaged absolute pressure field ⟨|P1|⟩ across channel width. Scale bar is 20 µm (c) streamlines illustrating the simulated streaming field along the channel width. (λ_{SAW} = 21 µm). Scale bar is 20 µm (d-g) Experimental visualization of particles' behavior (top view). Scale bar is 100 µm.

Size-dependent behavior of particles

To investigate the size-dependent nature of the diffractive driven mechanisms, here we focus on the central region of the channel, between the peripheral streaming and beyond the extent of the lobe streaming. The present literature predominantly discusses two main behaviors in a TSAW driven system [3]. These include particles drifting along TSAW propagation direction and particle swirling in continuous vortices, however, the periodic trapping of particles induced by TSAW is yet to be fully elucidated. The acoustophoretic mechanisms, discussed above, can cause particles to display three distinct responses as their relative size varies. These include drifting in the direction of SAW propagation, patterning in stable locations, and continuous motion in circular trajectories along with two transitional regions (Fig. 2) [4]. At a constant frequency and power, particles below a certain size only experience streaming, though their behavior shifts to the first transitional region, i.e. Streaming and Patterning (Fig. 2c-e), as their size increases, then to the patterning dominant region (Fig. 2f). By further increasing of the size, particles represent the second transitional behavior, i.e. patterning and drifting (Fig. 3g), and beyond a second critical diameter, they only experience drifting (Fig. 2h).

Conclusion

The inherent diffractive effects along with the size-dependent acoustic mechanism interplay leads to a diversity in particle behavior within SAW-driven systems. A deeper understanding of these phenomena lays foundational building blocks that unlock new applications that are currently not feasible.

Literature

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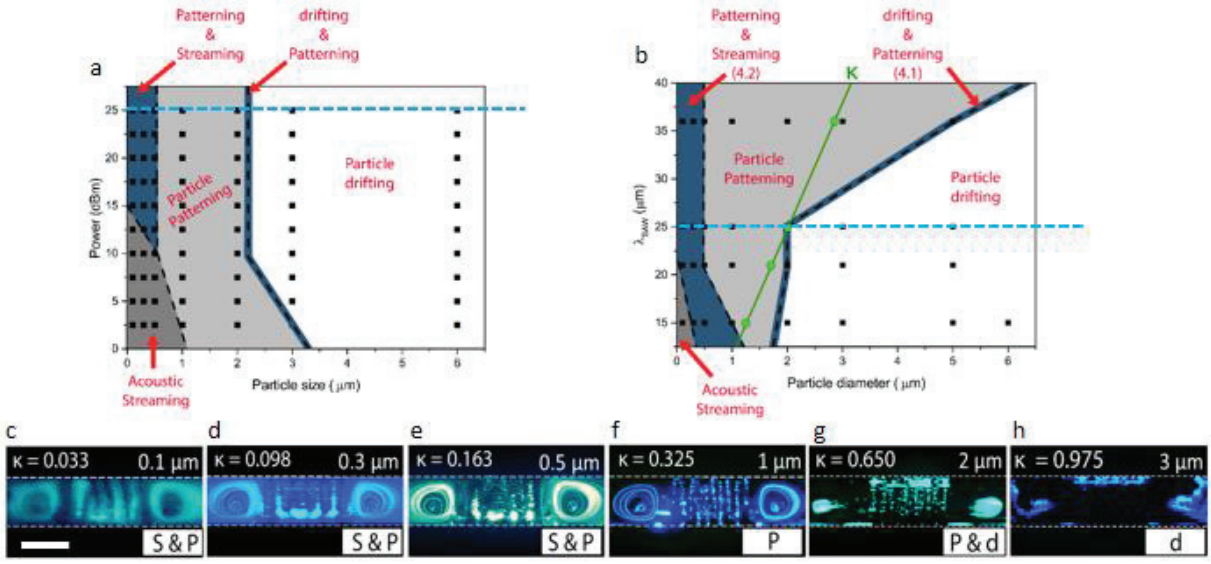

Figure 2: The transitional behavior of particles influenced by particle diameter as a function of (a) applied power and (b) wavelength of TSAW, where each region (indicated by different colour) shows the dominant mechanism governing particle behavior. Black squares represent the conducted experiments, dashed lines show the transitional borders, green circles represent the cross-over from streaming dominated to radiation dominated behaviour predicted based on κ value (the dimensionless constant) as explained by Skowronek et al. [3]. The blue dashed lines show the location of (c-h) experimental observations illustrating the transition in particle behavior as their diameter increases from 0.1 μm to 3 μm. S, P and d are streaming, patterning and drifting respectively. Scale bar is 200 μm.