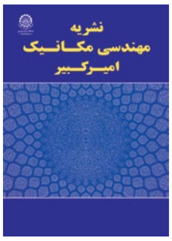

Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 53(1) (2020) 1-3
DOI:

A Review of Studies on the Motion of Particles Under the Influence of Acoustic Waves in Microfluidic Systems

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ABSTRACT: The use of acoustic waves to control and manipulate suspended particles in the fluid has attracted particular attention in the last two decades. The propagation of acoustic waves in the fluid medium may affect the suspended particles mainly by two factors. The initial effect of wave propagation directly acts on the particles and causes the application of force on them via the fluid medium. In viscous fluid, due to the wave attenuation and the formation of velocity gradients due to viscosity, the secondary fluid streaming form that can indirectly affect the particles. Due to the wide applications of this technology in medical and biological fields and the complexity of the experimental work in micrometer dimensions, there is a growing demand for analytic studies and theoretical insights on this subject. The subject of the present paper is a review on the analytical studies of the mechanisms affecting the movement of particles under the influence of acoustic waves propagating in the microfluidic systems. This review article presents a historical review of the early theories for the calculations of acoustic radiation forces and also the progress of these theories up to the now. Also, a review of the existing research results, problems and limitations, and the effect of different parameters on estimating these results are presented.

Review History:

Received:
Revised:
Accepted:
Available Online:

Keywords:

Acoustofluidics
Acoustic radiation force
Acoustic interaction force
Acoustic streaming

1. INTRODUCTION

The separation and manipulation of suspended particles in microfluidics has gained considerable attention during the past years. This manipulation can be performed using a variety of methods. Some examples of these methods are magnetophoresis, electrophoresis, and di-electrophoresis. In these methods, the particles are controlled and manipulated based on their certain specific physical properties. The use of acoustic forces, as another mean for manipulating particles, has received special attention due to its prominent capabilities. Unlike the aforementioned methods, the use of acoustic waves is not constrained by the specific physical properties of particles. The acoustic waves can manipulate all kinds of particles if they differ with the host fluid in acoustical properties. Moreover, the acoustic waves are noninvasive and do not alter the viability of the biological particles. The applied frequency can vary from kHz to MHz to capacitate the acoustic waves to cover a wide variety of particles. Studying the method of acoustic forces can be helpful in effective utilization of this method in sorting, mixing, separating and manipulation of particles. Fig. 1 illustrates a schematic of using ultrasonic acoustic waves in the separation of particles. As shown in this figure, according to different acoustical properties of different particles, type-A particles gather at the pressure node while type-B particles migrate to the wave antinode.

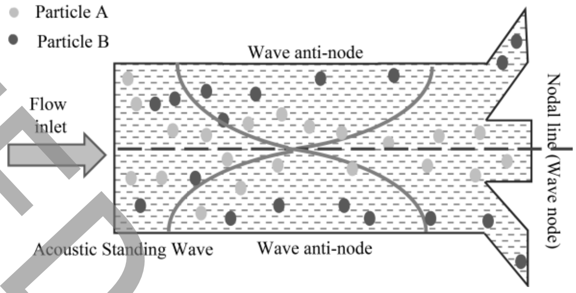

Fig. 1: Particle separation by acoustic radiation force

The study of the wave propagation and acoustic forces in the fluid has a long historical background. This classical field has found a new character in today's research activities as acoustophoresis which means the study of particles motion under the influence of ultrasonic acoustic waves. In acoustophoretic manipulation, the particles are mainly influenced by the acoustic radiation force and acoustic streaming. The acoustic radiation force is a result of the momentum transfer from the wave to the particle, while the acoustic streaming is due to momentum transfer from the wave to the fluid [1-3].

2. ACOUSTIC RADIATION FORCE

An exposed object to sound waves experiences a force from the wave; the so-called acoustic radiation force. The acoustic radiation force arises from the scattering of the wave of the object surface due to the difference in acoustical properties of the object and the surrounding fluid [4]. This force arises from the nonlinear properties of the wave

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propagation in fluid medium and therefore is considered as a nonlinear effect.

The acoustic radiation force values may vary in orders of magnitude with changes in the particle type [4-8]. Furthermore, non-spherical particles may experience acoustic radiation torque due to their geometrical asymmetry. In this case, the acoustic radiation force direction deviates from the wave propagation direction [9].

In viscous fluids, the formation of secondary acoustic streaming around the particle may have a significant contribution in acoustic radiation force [3, 10, 11]. Depending on the boundary layer thickness in comparison with the particle radius, the effect of corrective terms on the evaluation of acoustic radiation force will be different. The thermal effects, depending on the thermal boundary layer thickness, can also emerge in the acoustic radiation force as additional force terms [12-14]. According to the previous research results, the thermo-viscous effects can remarkably change the acoustic radiation force and even change its sign [15].

3. ACOUSTIC INTERACTION FORCE

The radiation forces are generally divided into primary and secondary forces. The primary radiation forces arise from the scattering of the incident wave by the particles and act on the particles irrespective of their relative positions. On the other hand, the acoustic interaction forces or the secondary forces are due to the interactions of particles in the sound field. These forces arise from the scattering of the waves which are once scattered by other particles [16]. Fig. 2 shows the schematic of the interaction between a pair of particles via the scattered wave field.

In the case of large distances between the particles, the secondary radiation forces are relatively small and the particles are mainly driven by the primary radiation forces [17]. However, for the case of small distances between the particles, the secondary forces are considerable and can even dominate the particles motion. Viscosity, in addition to the weakening of the scattered waves, causes the formation of shear waves in the viscous boundary layer around the particles and hence affects the interaction forces. The streaming formed due to viscosity can remarkably increase the interaction force [18].

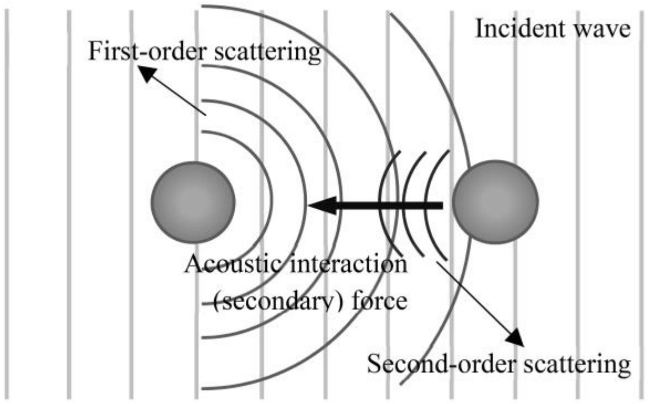

Fig. 2: Particle interactions in an acoustic field

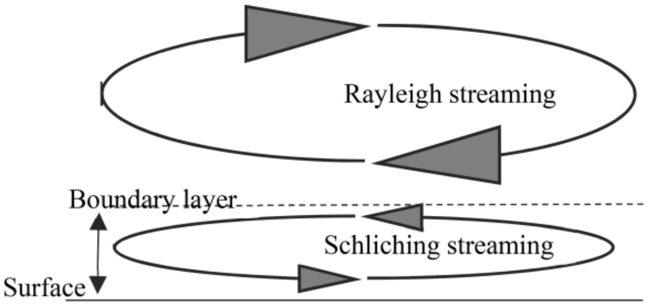

Fig. 3: Rayleigh and Schliching streamings

4. ACOUSTIC STREAMING

The acoustic streaming is an additional steady flow field which is formed apart from the oscillating motion of the wave in fluid. Similar to the acoustic radiation force, the acoustic streaming is a second order effect and results from the nonlinear terms of the governing equations.

The acoustic streaming can be subdivided into two main groups. The first group includes the boundary driven streamings including Rayleigh [19] and Schliching [20] streamings as schematically shown in Fig. 3. Rayleigh streaming is due to the relative velocity of the oscillating fluid with respect to the surrounding boundaries. Rayleigh streaming results from the extreme velocity gradients in the acoustic boundary layer and describes the fluid flow out of this layer. The streaming inside the boundary layer is called Schliching streaming. The second group of the streamings which are formed due to the large amplitude attenuation of sound waves in the fluid bulk are called Ecart streaming [21]. Specifically, when the wave attenuates as a consequence of momentum transfer to the wave, such an energy transformation emerges as the formation of a steady flow called bulk dissipative driven streaming.

5. CONCLUSIONS

The factors influencing the particles exposed to the acoustic waves can generally be classified into two main types. The first type which is due to the direct influence of the sound wave on the particles includes the primary and the secondary radiation forces. The primary radiation forces arise from the interaction of the incident wave with the particles and cause the particles to migrate into wave nodes/loops depending on their properties. The secondary radiation forces appear due to the interactions between the particles and cause the particles to attract or repel each other depending on their configuration related to the wave direction. The second type is related to the indirect effect of the waves on the particles. The propagation of the waves produces a series of secondary streamings which affect the particles via drag forces.

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