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Historical perspective

Acoustic levitation of liquid drops: Dynamics, manipulation and phase transitions

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ABSTRACT

The technique of acoustic levitation normally produces a standing wave and the potential well of the sound field can be used to trap small objects. Since no solid surface is involved it has been widely applied for the study of fluid physics, nucleation, bio/chemical processes, and various forms of soft matter. In this article, we survey the works on drop dynamics in acoustic levitation, focus on how the dynamic behavior is related to the rheological properties and discuss the possibility to develop a novel rheometer based on this technique. We review the methods and applications of acoustic levitation for the manipulation of both liquid and solid samples and emphasize the important progress made in the study of phase transitions and bio-chemical analysis. We also highlight the possible open areas for future research.

Contents

1. Introduction

Foreign objects, including liquid drops, gas bubbles, solid particles etc., in a fluid can experience a steady time-averaged force when irradiated by a sound field, which is referred to as acoustic radiation force [1]. The intriguing phenomenon of dust particles forming a ring-like pattern in a glass tube, under the effect of a standing sound wave was reported by Kundt et al. in 1866 [2]. Afterwards, to understand the phenomenon, the acoustic radiation force on small particles, say, $r \leq \lambda$ (r is the radius of particle and λ is the sound wavelength), has been extensively studied since 1930s. In 1934, King proposed the

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acoustic radiation force for spherical incompressible particles in acoustic fields [3]. In 1962, Gor'kov developed a more general theory based on the acoustic force potential U_{ac} suitable to compressible particles, which can be written as [4].

$$U_{ac} = \frac{4\pi}{3} r^3 \left[f_1 \frac{1}{2\rho_M c_M^2} <p^2> - f_2 \frac{3}{4} \rho_M <v^2> \right] \quad (1)$$

$$f_1 = 1 - \frac{k_P}{k_M} \quad (2)$$

$$f_2 = \frac{2\left(\rho_p - \rho_M\right)}{\left(2\rho_p + \rho_M\right)} \quad (3)$$

where p and v are the sound pressure and particle velocity, c_M is sound velocity in the medium, k and ρ are compressibility and density, the subscripts M and P represent "medium" and "particle", respectively. Eqs. (1)–(3) built the relation between the acoustic radiation force, the sound field and the properties of the system, which also suggest that the acoustic force is sensitive to the compressibility difference between the particle and medium. Due to the elimination of the difference between k_p and k_m, the acoustic levitation in liquid medium is more challenging, though manipulation of micro-sized particles using MHz sound wave in acoustofluidic systems is possible [5]. It is well known that, acoustofluidics is already strongly impacting the *soft matter* field, ranging from particle aggregation studies [6] to 3D manipulation [7]. Here, we mainly study the acoustic levitation in air. We do not put emphasis on MHz acoustic resonator at the moment because it can only obtain micro-scale particle manipulation [8], but focus on the levitation which works at 20 k ~ 100 k Hz using power ultrasound [9].

1.1. Single axis levitator

For the acoustic levitation in air, the potential U_{ac} can be simplified as

$$U_{ac} = 2\pi r^3 \left[\frac{<p^2>}{3\rho_0 c_0} - \frac{\rho <v^2>}{2} \right] \quad (4)$$

where, ρ_0 is the density of air and c_0 is the sound velocity in air. The simplest and most popularly used acoustic levitator is usually called the 'single-axis levitator' which consists of a transducer and a reflector [10], as illustrated in Fig. 1(a). The samples, either solid or liquid, can be levitated at the pressure nodes of the sound field, each of which is separated by a distance of $\lambda/2$ [11]. It should be noted that it may exhibit different levitation performance at different pressure nodes. For the levitation of a liquid droplet, the goal is not simply to balance gravity. A force balance at the droplet surface must be obtained. The acoustic radiation pressure on the droplet is not uniform, usually positive (compression) at the polar area while negative (suction) at the equator, as illustrated in Fig. 1(b). The droplet will, in turn, adjust its surface curvature to adapt the radiation pressure. Meanwhile, the Bernoulli effect arising from the acoustic streaming may alter the force balance on the levitated sample and bring additional instability. To enhance the levitation ability and stability, the reflector [12] or both reflector and emitter [13] were often made concave. In general, there is a size limit of ~$\lambda/2$ for the sample that can be stably levitated which is determined by the maximum size of the potential well of single acoustic levitator. The typical sample size for levitation is around $\lambda/4$ ~ $\lambda/3$, which has been reported in previous experiments [14].

1.2. General applications of acoustic levitation

Since contamination from the container walls can be avoided and considering experimental simplicity, acoustic levitation has a wide range of applications in drop dynamics [12], biology [16,17], analytical chemistry [18–20], solidification [21] and pharmacy [22]. The main advantages of acoustic levitation over other levitation techniques, such as optical tweezers [23] both electrostatic [24] and electromagnetic, is that transparency and electro-magnetic properties of the levitated materials [25] are not required, which make it suitable for a broader range of materials. It should be pointed out that acoustic levitation is excellently amenable to soft matter, including complex drops, bubbles, foams, emulsion etc. Due to their softness, they can easily adapt their shape to the sound field, leading to good levitation stability. On the other hand, the mechanical or rheological properties of the levitating sample are reflected from its response to the sound field [26,27]. This is desirable for the study of viscoelasticity and relaxation of soft matter.

The unique environment provided by acoustic levitation, i.e., container-free condition and droplet internal flow, may result in novel or unusual physical/chemical effects. For instance colliding and mixing of acoustically levitated droplets gives a homogeneous system in 3–4 s [28], as illustrated in Fig. 2. The mixing was accelerated by at least an order of magnitude over that of three-dimensional diffusion, Moreover, by combining with other remote spectrum techniques [29], acoustic levitation provides an ideal platform to study the physical/chemical processes in the soft matter systems in contact-free condition, which is extremely beneficial to elucidate the effect of solid walls on these processes.

As compared with use of optical tweezers which can only manipulate small particles from tens of nanometers to tens of micrometers and is adept to the measurement of thermal-scale forces and weak interaction [23], acoustic levitation can produce stronger force trapping in larger spatial scale, therefore is competent to manipulate millimeter-sized drops. The working frequency of this technique is normally around tens to hundreds kHz, far below the frequency of Brillouin

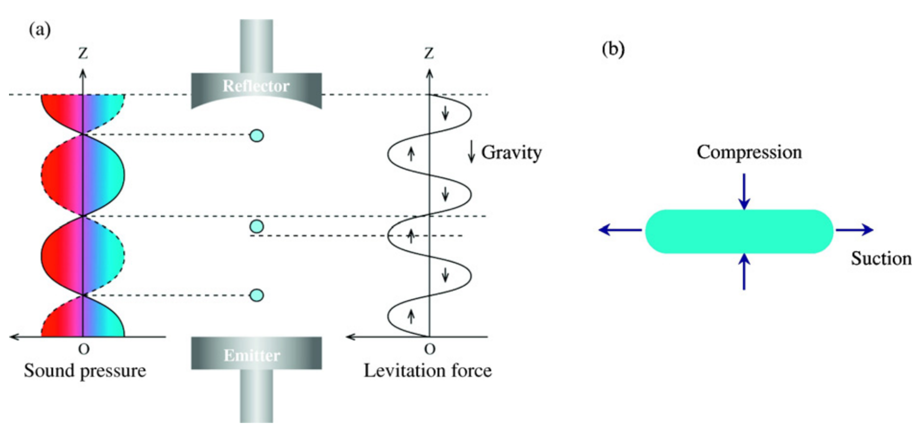

Fig. 1. (a) Schematic view showing the principle of acoustic levitation of a single-axis levitator. The samples can be levitated at the pressure nodes. (b) Illustration of acoustic radiation pressure distribution on a levitated liquid droplet. The arrows indicate the direction of force caused by acoustic radiation.