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Contactless and non-invasive delivery of micro-particles lying on a non-customized rigid surface by using acoustic radiation force

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ABSTRACT

In the existing acoustic micro-particle delivery methods, the micro-particles always lie and slide on the surface of platform in the whole delivery process. To avoid the damage and contamination of micro-particles caused by the sliding motion, this paper deals with a novel approach to trap micro-particles from non-customized rigid surfaces and freely manipulate them. The delivery process contains three procedures: detaching, transporting, and landing. Hence, the micro-particles no longer lie on the surface, but are levitated in the fluid, during the long range transporting procedure. It is very meaningful especially for the fragile and easily contaminated targets. To quantitatively analyze the delivery process, a theoretical model to calculate the acoustic radiation force exerting upon a micro-particle near the boundary in half space is built. An experimental device is also developed to validate the delivery method. A 100 μm diameter micro-silica bead adopted as the delivery target is detached from the upper surface of an aluminum platform and levitated in the fluid. Then, it is transported along the designated path with high precision in horizontal plane. The maximum deviation is only about 3.3 μm. During the horizontal transportation, the levitation of the micro-silica bead is stable, the maximum fluctuation is less than 1 μm. The proposed method may extend the application of acoustic radiation force and provide a promising tool for microstructure or cell manipulation.

1. Introduction

Nowadays, directed and controllable delivery of micro-particles or macromolecules to a target position is of major importance for the rapidly growing areas of proteomics [1,2] and micro-assembly [3,4], particularly in massively parallel single-cell manipulation and characterization [5]. Because micro-components and cells are very fragile and easily contaminated, a contactless and non-invasive method to deliver the target on rigid surfaces is highly desirable. Several acoustic applications have been developed to manipulate these targets for their contactless, non-invasive characteristics and parallel processing capabilities. Recently, particle or cell separations and alignments have been achieved using acoustic radiation force [6–8]. More complicated particle or cell manipulations also have been obtained by progressively shifting the relative phase between two opposing interdigital transducers (IDTs) [9,10] or by varying the frequency of both electrodes to change the wavelength [5,11].

However, a less desirable effect of the above systems is that the micro-particles settle onto a lower surface due to gravity [12,13], making the micro-particles slide on the lower surface during the delivery process. Therefore, an additional driving force is needed to counteract the friction between the micro-particles and the lower surface. Besides, the sliding motion on the lower surface may cause particle damage and contamination. To overcome these limitations, Manneberg et al. (2008) applied wedge transducers instead of IDTs in microfluidic chips to successfully aggregate particles and cells away from the lower surface [12,13], but further manipulation has not yet been achieved. Courtney et al. (2011) designed and manufactured a compact acoustic manipulation device in which an additional transducer was used as the lower surface to avoid contact between the particles and the lower surface [14,15]. In our previous study [16], we presented a methodology which was able to achieve controllable transportation of micro-particles in two dimensions without a lower surface. Transportation was achieved in the vertical plane and the force of gravity on the particles was overcome by acoustic radiation force.

However, the existing methods mentioned above are all inappropriate for most situations for the following reasons. The general object to be delivered is on a surface, such as a culture dish or a work table of a micro-assembly system, but not a customized

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surface, and the delivery process required is in the horizontal, not the vertical, plane. Moreover, the object initially adheres to the lower surface and needs to be trapped and levitated before being transported.

To overcome these limitations, we propose a novel acoustic method to deliver micro-particles which are initially located on a non-customized rigid surface. The delivery process contains three procedures: detaching the micro-particles from the rigid surface, freely and precisely transporting them in the horizontal plane, and landing them to the target position on the surface. To quantitatively analyze the three procedures, a theoretical model is built to calculate the acoustic radiation force exerting upon a micro-particle located near the boundary in half space. Based on the theoretical model, the acoustic radiation force in the delivery process is calculated and analyzed. The quantitative relationship between the node movement displacement and phase shift step in the transportation procedure in the horizontal plane is also investigated. Furthermore, an experimental device is developed and a series of experiments are conducted to validate the contactless and non-invasive delivery method. A micro-silica bead adopted as the delivery target in the experiments is successfully detached from the rigid surface, precisely transported along the designated path in the horizontal plane, and landed to the target position on the surface. The acoustic radiation force generated is in tens of nano-Newton and has advantages of being contactless, non-invasive, and controllable.

2. Experimental setup

Fig. 1a shows a schematic diagram of the experimental setup, consisting of three lead zirconate titanate (PZT) transducers, an aluminum platform with smooth rigid surface and a glass tank which is filled with deionized water. Three PZT transducers with a resonant frequency of 1.67 MHz are used to generate a standing wave field, whose radiating surface is rectangular with a width of 10 mm and a height of 25 mm. The PZT transducers are installed in an aluminum stage such that the incident angle of each sound beam axis is 60°. The three sound beam axes pass through the center O of the rigid surface, and the angle between the projections of every two sound beam axes in the horizontal plane is 120°. The distance d_T between the centers of every two PZT transducers is 45 mm. The glass tank is very large and the PZT transducers are arranged at the center of the glass tank. These features and the position arrangement minimize the reflections of the incident waves except those from the rigid surface, and make the sound field controllable. Continuous sinusoidal voltage signals with adjustable amplitude and phase are applied to the PZT transducers. A CCD camera is used to record the experimental results. The experimental setup is shown in Fig. 1b.

3. Theoretical model

The mechanism of the acoustic micro-particle delivery method is described in Fig. 2. Three plane waves come from three directions in the water with the same incident angles, α, to a plane rigid surface and a rigid micro-particle located near the surface in the central region of the sound field. The rigid surface acts as a reflector, so three reflected plane waves always exist and have the same amplitude as the incident plane waves. The incident plane waves and the reflected waves would be scattered by the rigid micro-particle. Moreover, the scattering wave from the rigid micro-particle would also be reflected by the rigid surface and the reflected wave can be seen as an additional scattering wave from the image of the rigid micro-particle.

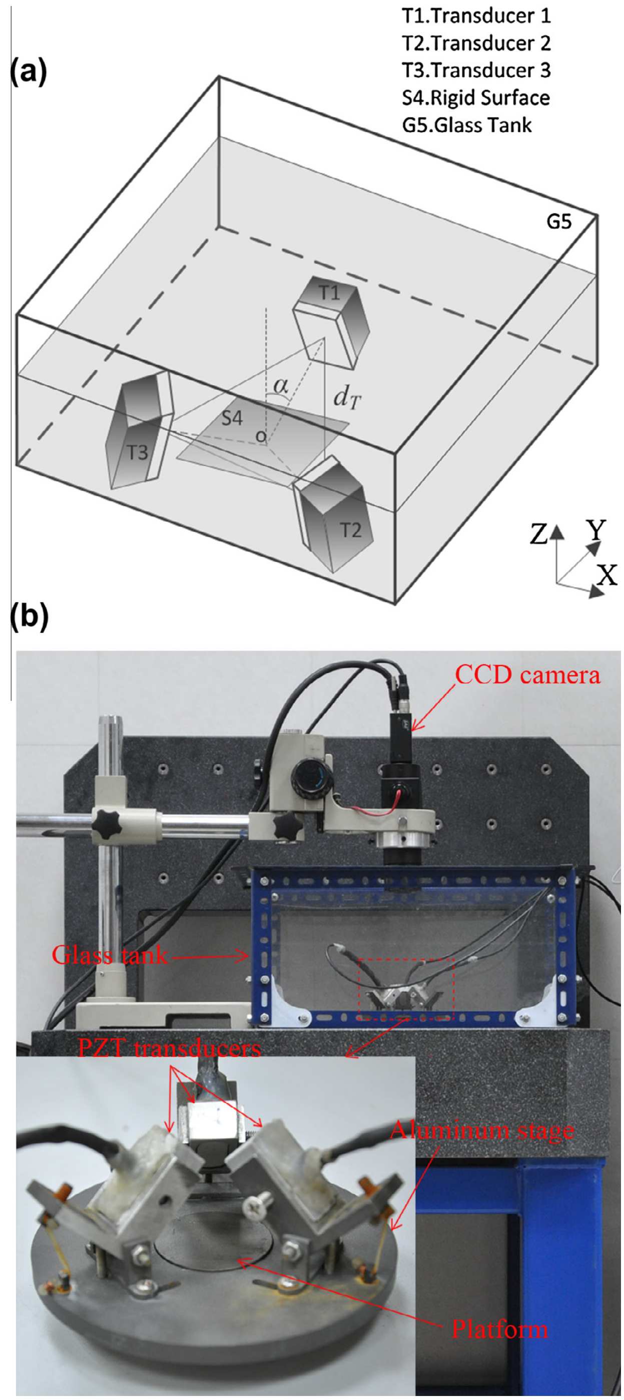

Fig. 1. Experimental setup for acoustic delivery of micro-particles lying on a non-customized rigid surface. (a) A schematic diagram of the experimental setup, where $\alpha = 60°$ and $d_T = 45$ mm. (b) A photo of the experimental setup.

3.1. The distribution of pressure nodes in half space

Considering the much smaller size of the rigid micro-particle compared with the wavelength of incident plane waves, the rigid micro-particle would not change the distribution of pressure nodes and anti-nodes in the sound field. Thus, the distribution just depends on the incident plane waves P_j^{inc} and the reflected waves P_j^{ref} given as:

$$P_j^{\text{inc}} = P_0 \exp\left\{ikr[\cos(\pi-\alpha)\cos\ \theta + \sin(\pi-\alpha)\sin\ \theta\ \cos(\varphi-\beta_j)] + i\gamma_j\right\} \quad (1)$$