Finite Element Analyses of Working Principle of the Ultrasonic Needle-Droplet-Substrate System for Multiple-Function Manipulation

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Abstract. Convenient and high-efficiency manipulation of nanoscale materials has huge potential applications in nano assembly and biomedical technology. We have reported an ultrasonic needle-droplet-substrate system to aggregate and then transport the nanoscale materials freely at the interface between the substrate and water droplet. In the manipulation method, the ultrasonic needle is inserted into the water droplet of nanoscale material to generate a controlled ultrasonic field for the manipulations. In this paper, we report the detailed method and results of FE (finite element) analyses for the investigation of working principle of the manipulation system. The FE analyses show that the ultrasonic needle can generate an acoustic streaming field around the ultrasonic needle to implement the nano aggregation and transportation. The computational results can well explain the experimental phenomena of multiple-function manipulation.

Keywords: Finite element · Ultrasonic needle-droplet-substrate system · Manipulation · Multiple-function

1 Introduction

Manipulation of nanoscale materials has huge potential applications in the fabrication of nano-sensing materials and nano-electrode, nano decoration, micro/nano assembly [1–3], etc. Several existing methods for the manipulation of micro/nanoscale materials have been reported. They include the magnetic method [4, 5], dielectrophoresis method [6, 7], optical method [8, 9], and acoustic method [10, 11]. Compared to other methods, the acoustic method has the following merits. It is not selective to the material properties of manipulated samples, and has little thermal damage to the manipulated samples (in some methods). Its devices can be very simple and compact. Therefore, the acoustic method is very competitive in nanoscale material manipulations.

In order to implement the aggregation and transportation of nanoscale materials at a droplet-substrate interface by the same ultrasonic device, an ultrasonic needle-droplet-substrate system, which can aggregate and then transport the nanoscale materials freely at the interface between the substrate and water droplet, was proposed [12, 13]. In the manipulation method, the ultrasonic needle is inserted into the water droplet of nanoscale material to generate a controlled ultrasonic field for the manipulations. This new strategy for multiple-function manipulation of nanoscale materials, combined with other technologies, has potential applications in nano assembly, biomedical technology and so on.

In this paper, we report the detailed method and results of FE (finite element) analyses for the investigation of working principle of the manipulation system. The FE analyses show that the ultrasonic needle can generate an acoustic streaming field around the ultrasonic needle to implement the nano aggregation and transportation. The computational results can well explain the experimental phenomena of multiple-function manipulation. The FE analyses method also provides an effective way to design and optimize the multiple-function manipulation system.

2   Experimental Setup and Manipulation Functions

Figure 1 shows the experimental setup of the ultrasonic needle-droplet-substrate system for multiple-function manipulation nanoparticles. The experimental setup consists of three main components: ultrasonic needle, vibration transmission rod (VTR) and piezoelectric plate. The ultrasonic needle made of fiberglass is bonded onto the tip of the VTR by the 502 glue, the VTR made of stainless steel is bonded onto the edge of the long side of the piezoelectric plate by epoxy resin adhesive, and the VTR's end is fixed with a special fixture. The VTR has a uniform diameter of 1 mm, and is 26 mm long out of the piezoelectric plate. The ultrasonic needle and the piezoelectric plate are in the same plane, the ultrasonic needle has a uniform radius of 10 μm, and is 3 mm long, the angle between the VTR and the ultrasonic needle is about 90°. The length, width and the thickness of the piezoelectric plate are 20 mm, 10 mm and 0.78 mm, respectively. The piezoelectric constant d_{33}, electromechanical coupling factor k_{33}, mechanical quality factor Q_m, dielectric dissipation factor $tan\delta$, and density are 200×10^{-12} C/N, 0.60, 800, 0.5%, 7450 kg/m^3, respectively. The piezoelectric plate is used to generate the vibration, which passes through the VTR to excite the ultrasonic needle. The droplet is formed by DI water and ultrasonically dispersed nanoscale samples, and the ultrasonic needle can be positioned by the xyz platform. In the experiments, Si nanoparticles with a diameter of 500 nm was used as the manipulated sample, and the ultrasonic needle, inserted into the water droplet, was perpendicular to the substrate made of silicon. In the manipulation, the ultrasonic needle was moved to the adjacent of the droplet-substrate interface, on which there were nanoscale samples, to carry out the manipulation.

Images *a–d* in Fig. 2 show a multiple-function manipulation process for the Si NPs on the silicon substrate surface. In the experiments, the operating frequency and voltage are 75.5 kHz and 25 V$_{p-p}$, respectively. In image *a*, the Si NPs are uniformly dispersed in the water droplet. The micro-size nano spot in image *b* is formed by 120 s

sonication. From image *b* to *d*, the aggregated micro-size nano spot is transported freely at the interface between the silicon substrate and water droplet.
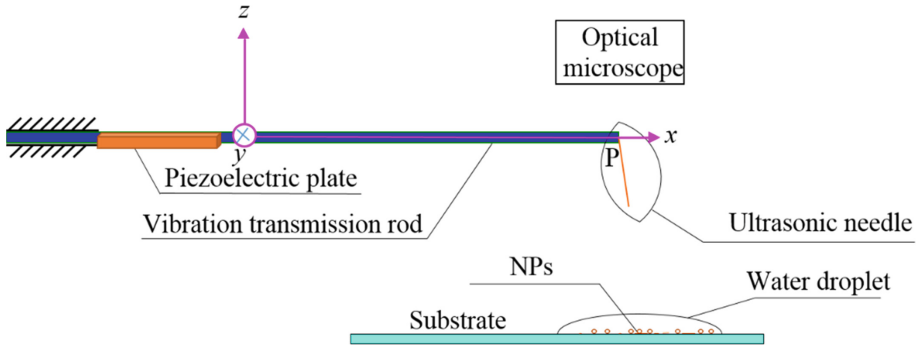

Fig. 1. Schematic diagram of the ultrasonic needle-droplet-substrate system for the multiple-function manipulation.
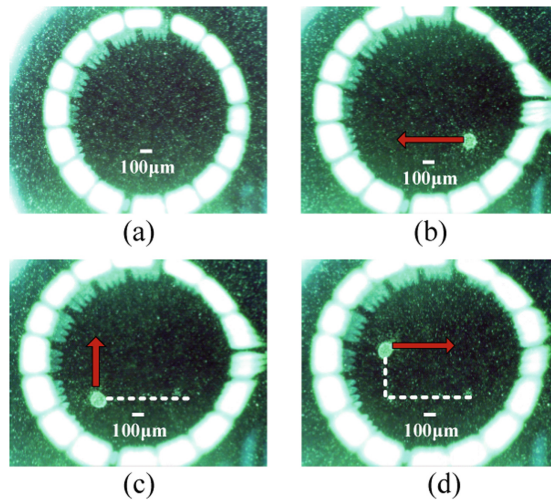

Fig. 2. Aggregation and transportation of the micro-size nano spot at the interface between the silicon substrate and water droplet.

In the experiments, the orthogonal vibration velocities at the ultrasonic needle's root V_x, V_y and V_z were 5.2 ∠ −13.8° mm/s, 61.6 ∠ −12.5° mm/s and 2.2 ∠ 172.5° mm/s, respectively. As the magnitude of the y-directional vibration velocity was much larger than that of the x- and z-directional vibration velocities, vibration trajectory at the ultrasonic needle's root was approximately linear.

3   FE Computational Model and Method

In order to investigate the manipulation mechanism, ultrasonic vibration and the acoustic streaming of the ultrasonic needle-droplet-substrate system were computed and analyzed by the finite element method (FEM). A mathematical-physical model and meshed FEM model used in the computation are shown in Fig. 3. The boundary conditions of the acoustofluidic field in the ultrasonic needle-droplet-substrate system are shown in Fig. 4. The computation was accomplished by software COMSOL Multiphysics. The spatial gradients of the Reynolds stress and mean 2nd pressure are the driving force of the acoustic streaming. Detailed method for the acoustic streaming computation as follows [14–16].

$$F_j = -\partial \langle \rho_0 u_i u_j \rangle / \partial x_i \tag{1}$$

$$\overline{p_2} = \frac{1}{2\rho_0 c_0^2} \frac{B}{A} \langle p^2 \rangle \tag{2}$$

$$\rho_0 (\overline{u}_i \partial \overline{u}_j / \partial x_i) = F_j - \partial \overline{p}_2 / \partial x_j + \eta \nabla^2 \overline{u}_j \tag{3}$$

where u_i and u_j are the vibration velocities of the sound field, ρ_0 is the fluid density without sound field, c_0 is the sound speed, p is the sound pressure (the first order), $\frac{B}{A}$ is the nonlinear parameter of the acoustic medium, F_j is the spatial gradient of the Reynolds stress, $\overline{p_2}$ is the mean 2nd pressure, η is the shear viscosity coefficient of the acoustic medium, and $< >$ represents the time average over one time period.
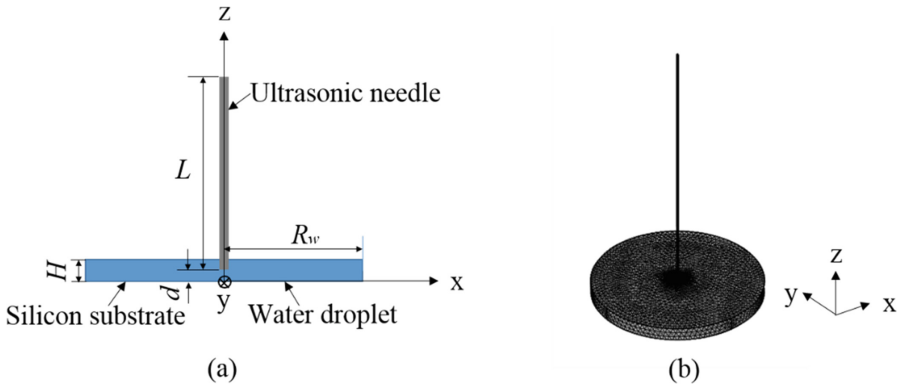

Fig. 3. (a) Math-physical model for the ultrasonic needle-droplet-substrate system. (b) Meshed model for the ultrasonic needle-droplet-substrate system.
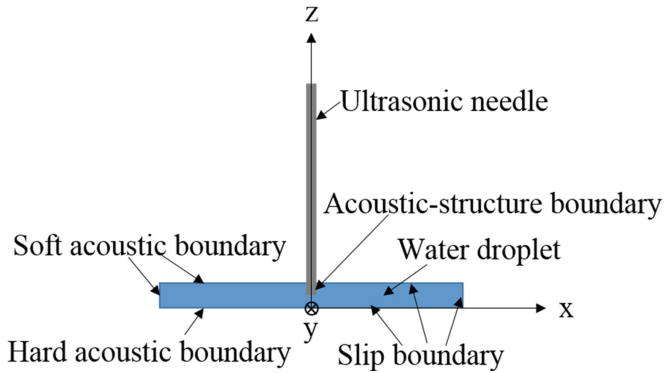
Fig. 4. Boundary conditions for the acoustofluidic field of the ultrasonic needle-droplet-substrate system.

4   Results and Discussion

The parameters of the ultrasonic devices and experimental system, used in the FEM computation, are listed in Table 1. The computed acoustic streaming on the substrate surface is shown in Fig. 5. It can be seen that the acoustic streaming on the substrate surface flows inward from the all-around, and the NPs are flushed to the location under the ultrasonic needle's tip. This explains the formation of the micro-size nano spot with a round shape shown in Fig. 2. The location of the acoustic streaming field is determined by the ultrasonic needle. Thus, the acoustic streaming can be shifted by moving the ultrasonic needle, which can be implemented by moving the ultrasonic device. Thus the micro-size nano spot can be transported freely at the droplet-substrate interface.

Table 1.   Parameters of the ultrasonic devices and experimental system.

Device dimensions & experimental setup parameters	Material constants
Ultrasonic needle length L (mm): 3	Water density ρ (kg/m^3): 1000
Ultrasonic needle radius R (µm): 10	Sound velocity in water c (m/s): 1500
Water film thickness H (mm): 0.15	Shear viscosity of water η (Pa s): 0.001
Water film radius R_W (mm): 3.5	Ultrasonic needle density (kg/m^3): 2200
Distance d between the ultrasonic needle's tip and substrate (µm): 40	Poisson's ratio of the ultrasonic needle: 0.3
Angle θ between the ultrasonic needle and the VTR (°): 90	Young's modulus of the ultrasonic needle (Pa): 7.4×10^{10}

In the above computation, the ultrasonic needle vibrates in the direction parallel to the substrate. Our computation shows that if the vibration of ultrasonic needle is not parallel to the substrate, the desired acoustic streaming field shown in Fig. 5 cannot be generated, which means that the aggregation and transportation functions cannot be realized by the device.
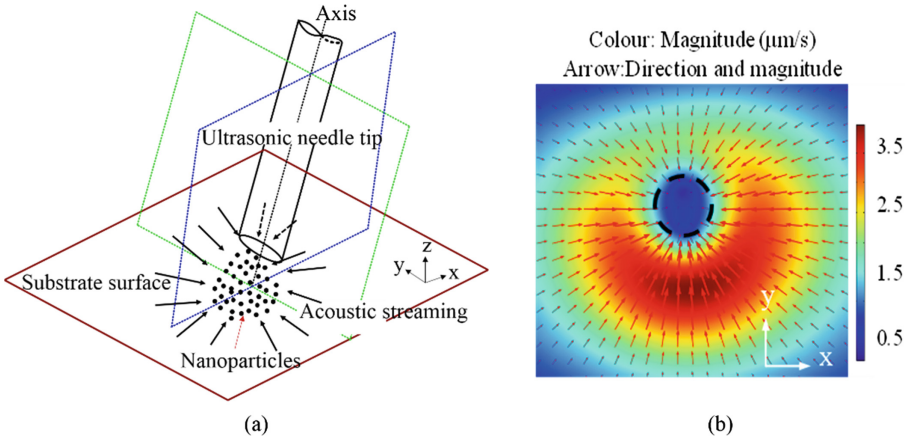
Fig. 5. (a) Schematic diagram of the acoustic streaming on the substrate surface. (b) Computational acoustic streaming on the substrate surface.

5   Summary

With the FEM computation, we have analyzed the aggregation and transportation mechanism in the ultrasonic needle-droplet-substrate system proposed by our group. The computation indicates that the acoustic streaming, which is generated by the linear vibration of the ultrasonic needle parallel to the substrate, can result in the multiple-function manipulation. The FE analyses method also provides an effective way to design and optimize the multiple-function manipulation system.

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