ROTATION OF NON-SPHERICAL PARTICLES IN SQUARE CHAMBERS USING ULTRASONIC STANDING WAVES

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Summary The acoustic radiation torque is used to rotate non-spherical particles. Therefore, a varying pressure field with a change of orientation of the corresponding potential force field is needed. Two methods based on amplitude modulation and phase modulation are presented. Successful experiments of both methods have been performed with in water suspended micro-particle clumps and a glass fibre (200 µm length). The resonator is a microfabricated device, excited by a piezoelectric transducer with a frequency in the MHz range.

INTRODUCTION

The ultrasonic micromanipulation is commonly used to position and move particles with the help of acoustic radiation forces. The method presented here allows the rotation of non-spherical particles using the acoustic radiation torque. The rotational manipulation of micro-particles in microfluidic devices is another step to expand the possible applications of ultrasonic micromanipulation. The rotation speed as well as the direction of rotation are parameters which could be controlled in order to precisely manipulate the particles. This technique is one of the promising tools which could be used for ultrasonically-driven micro-machines in lab-on-a-chip systems, orientation of fibers in microstructure constructions and positioning of micro-components.
Non-spherical particles experience a torque in an ultrasonic standing wave. Fibers shorter than one-fourth of the wavelength are constrained at the pressure node and are oriented perpendicular to the direction of wave propagation [1]. It is possible to use this acoustic radiation torque for a continuous rotation of objects. Therefore, a slowly varying pressure field with changing orientation of the corresponding potential well is needed. This is realized using amplitude modulation of two orthogonal standing waves. Another option is the excitation of a double mode by two sources and a slight frequency difference or a varying phase.

AMPLITUDE MODULATION

The rotation is based on the amplitude modulation of two superimposed orthogonal standing waves in x and y direction in a resonant square cavity. Oberti *et al.* [2] studied the different cases of the superposition used to generate a two-dimensional pressure field. The method is extended here to the amplitude modulation of the two orthogonal standing waves:

$$p_1 = A_x \cos(k\,x)\sin(\omega\,t)\ ;\ p_2 = A_y \cos(k\,y)\sin(\omega\,t) \tag{1}$$

with pressure p, amplitude A, wave number k, angular frequency ω and time t. For the calculation of the Gor'kov force potential [3] the mean square fluctuation of the pressure and the velocity is derived from Eqn.1. The force potential is plotted for different amplitudes of A_x and A_y as shown in Fig.1.

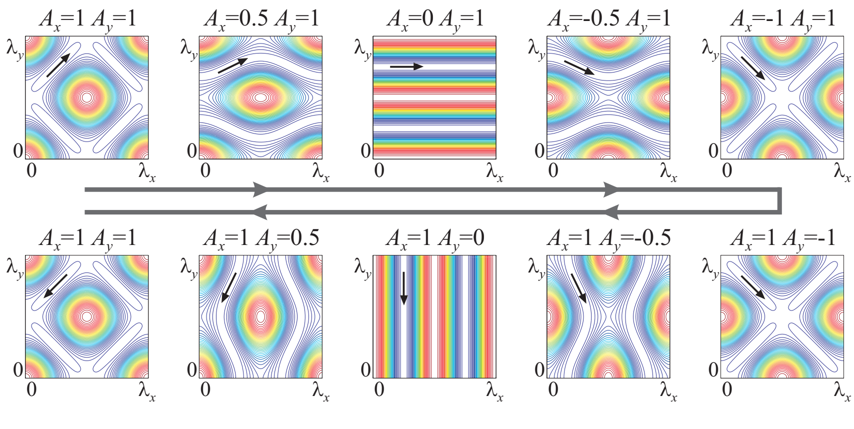

Fig. 1: Contour plot sequence of the Gor'kov force potential for a unit cell (one wavelength in x and y direction) as result of the amplitude change of two superposed cosine functions with identical frequency and phase. In the top row the term A_x varies from +1 to -1 and A_z stays constant. In the second part the term A_z varies from +1 to -1 and A_x stays constant. The red areas are potential maxima, the blue areas potential minima for a stiff and dense particle. The black arrow represents the orientation of a fiber in the force potential minima.

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By varying the amplitudes of the standing waves the orientation of the force potential minima could be rotated. If the sequence shown in Fig.1 is passed in the order shown by the gray arrow line the potential field rotates. The rotation will be a uniform rotation for sinusoidally varying amplitudes. The speed of rotation is governed by the frequency of the amplitude change. For one sequence, the object is performing a rotation of 180°. Therefore, the modulation frequency must be double the desired rotation frequency. The force potential fields in Fig.1 are shown for one wavelength. There are four spots were a rotation is possible whereas two are rotating clockwise and the other two are rotating counter clockwise. The rotating object could be stopped at any given angular position.

PHASE MODULATION

The simple phase modulation of two superimposed orthogonal standing waves in x and y direction (see Eqn.1) in a resonant cavity could not be used to induce rotation, as shown in [2]. The overlapping of two orthogonal modes leading to a double peak is required. For a perfectly square cavity, the two orthogonal modes exist at the exact same frequency. If the excitation or geometry leads to an asymmetry, the two modes are at slightly different frequencies. When damping is considered in the system, both peaks will overlap. This could be simplified to the following standing pressure fields

$$p_1 = A\,[\cos(k\,x)\sin(\omega\,t) + \cos(k\,y)\sin(\omega\,t - \alpha)]\ ;\ p_2 = A\,[\cos(k\,y)\sin(\omega\,t) + \cos(k\,x)\sin(\omega\,t - \alpha + \varphi)] \qquad (2)$$

where φ is the phase difference between the both standing pressure fields p_1 and p_2, which is controlling the rotation. The additional term α is coming from the phase difference in the double peak between the two orthogonal modes if the system is excited with the middle frequency of the double peak. If α is $\pi/2$ the rotation is uniform for a linear variation of the phase φ. For other values of α like $\pi/4$ the rotation gets non-uniform, leading to a faster angular velocity followed by slower during one rotation cycle. For a α of 0 no rotation is possible.

EXPERIMENTS

The device used for the experiments consists of a 3x3 mm^2 fluidic chamber etched into silicon and covered with a glass plate (see Fig.2a). The actuation is done through a 4x4 mm^2 piezoelectric crystal fixed at the back side of the device. The excitation of two orthogonally oriented strip electrodes, defined on the surface of the same piezoelectric transducer, leads to the required asymmetry. A two dimensional pressure field can be set up, assuming that the chamber depth (200 μm) is kept smaller than half of the acoustic wavelength in the fluid [2]. Both described rotation methods have been tested with particle clumps and glass fibers. Depending on the excited mode, the device was in general suitable for both rotation methods. The rotation with the amplitude modulation is depicted in Fig.2b with particle clumps formed out of 17 μm copolymer particles at a frequency of 1689 kHz. Fig.2c shows the rotation of a 200 μm long glass fiber. The actuation frequency was set to 1085 kHz with a maximum amplitude of 30 V. The speed of rotation could be increased up to about 30 rpm. Additionally, it was possible to stop the fiber at any given orientation and it was possible to inverse the rotational direction.

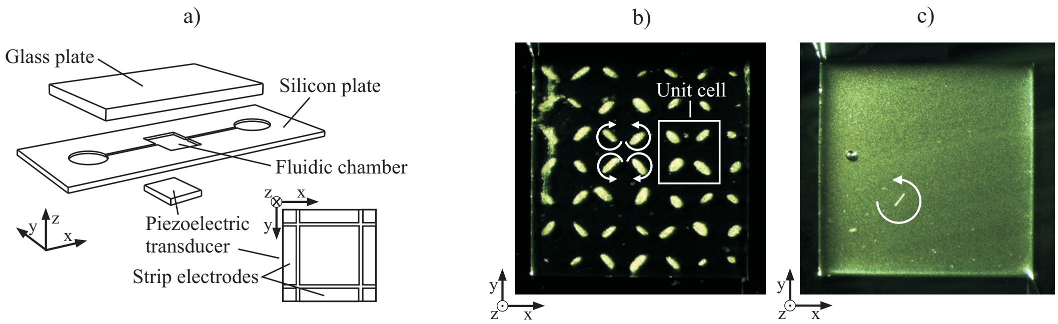

Fig. 2: a) Exploded view of the micromanipulation device with detail of piezoelectric transducer showing the strip electrodes for the excitation b) rotation of particle clumps (copolymer particles, 17 μm) with amplitude modulation at a frequency of 1689 kHz c) rotation of a glass fiber (length 200 μm, diameter 15 μm) with amplitude modulation at a frequency of 1085 kHz.

CONCLUSIONS

The rotation of non-spherical particles with ultrasonic standing waves using the acoustic radiation torque seems promising and opens new application fields. Both methods are useful for a continuous rotation and the object could be stopped at any given angle making it also suitable for alignment applications.

References

[1] Yamahira S. *et al.*: Orientation of Fibers in Liquid by Ultrasonic Standing Waves. *Jpn.J.Appl.Phys.* **39**: 3683-3687, 2000

[2] Oberti S. *et al.*: Manipulation of micrometer sized particles within a mircromachined fluidic device to form two-dimensional patterns using ultrasound. *J. Acoust. Soc. Am.* **121**: 778–785, 2007

[3] Gorkov L.P.: Forces acting on a small particle in an acoustic field within an ideal fluid. *Dokl. Akad. Nauk SSSR.* **140**: 88–92, 1961