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Investigation of two-dimensional acoustic resonant modes in a particle separator

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Abstract

Within an acoustic standing wave particles experience acoustic radiation forces, a phenomenon which is exploited in particle or cell manipulation devices. When developing such devices, one-dimensional acoustic characteristics corresponding to the transducer(s) are typically of most importance and determine the primary radiation forces acting on the particles. However, radiation forces have also been observed to act in the lateral direction, perpendicular to the primary radiation force, forming striated patterns. These lateral forces are due to lateral variations in the acoustic field influenced by the geometry and materials used in the resonator. The ability to control them would present an advantage where their effect is either detrimental or beneficial to the particle manipulation process.

The two-dimensional characteristics of an ultrasonic separator device have been modelled within a finite element analysis (FEA) package. The fluid chamber of the device, within which the standing wave is produced, has a width to height ratio of approximately 30:1 and it is across the height that a half-wavelength standing wave is produced to control particle movement. Two-dimensional modal analyses have calculated resonant frequencies which agree well with both the one-dimensional modelling of the device and experimentally measured frequencies. However, these two-dimensional analyses also reveal that these modes exhibit distinctive periodic variations in the acoustic pressure field across the width of the fluid chamber. Such variations lead to lateral radiation forces forming particle bands (striations) and are indicative of enclosure modes.

The striation spacings predicted by the FEA simulations for several modes compare well with those measured experimentally for the ultrasonic particle separator device. It is also shown that device geometry and materials control enclosure modes and therefore the strength and characteristics of lateral radiation forces, suggesting the potential use of FEA in designing for the control of enclosure modes in similar particle manipulator devices.

Keywords: Lateral radiation force; FEA; Particles

1. Introduction

The action of acoustic radiation forces on particles has been exploited in devices designed to manipulate particles. Such devices include particle separators and fractionators in which the nature of the acoustic field significantly influences the performance of the device. Therefore, in order to design ultrasonic devices reliably, the characteristics of the acoustic field must be considered.

These devices typically rely on the presence of a plane standing wave generated using a plate transducer. The resulting acoustic field is usually described one-dimensionally with the field varying in a direction normal to the transducer plate. Acoustic radiation forces result from these variations, and in a direction normal to the transducer. When the standing wave is generated within a fluid cavity containing a particle suspension, the particles experience an acoustic radiation force which depends on both the density and compressibility of the particles, allowing neutrally buoyant particles to be manipulated and filtered. This will typically move solid phase particles to the pressure

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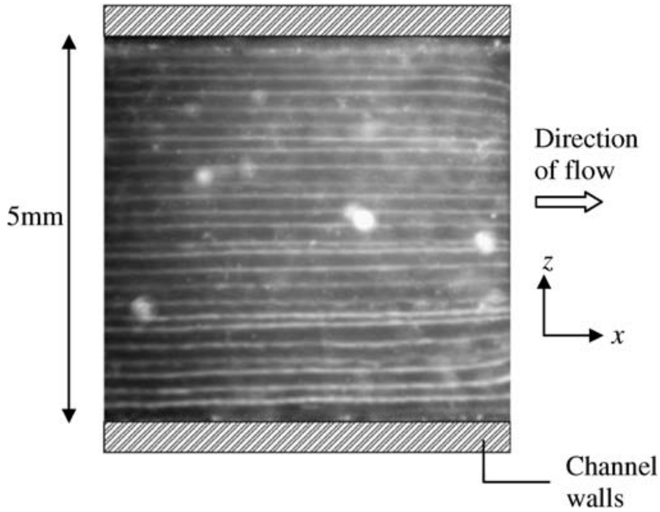

Fig. 1. Striated patterns observed using yeast for conditions of continuous flow-through.

node(s) and form a layer of concentrated particles. However, lateral movement of particles is frequently observed as variations within the acoustic field exist with the particles moving within the nodal plane to areas of high acoustic kinetic energy [1]. The lateral movement of particles can be attributed to lateral variations within the acoustic field which give rise to lateral acoustic radiation forces. The source of these variations is the subject of this paper.

Fig. 1 shows the effect of lateral forces on particles within a particle separation device. The image is taken looking down upon the device and in the axial (y) direction with the transducer located on the underside of the device and orientated in the xz plane. A half-wavelength standing wave is generated within a fluid layer and forms a pressure node along its centre plane, towards which particles move due to axial radiation forces. Within this image the effect of additional lateral forces can be seen where particles have moved to positions of high acoustic kinetic energy and have formed a striated pattern. This reveals the effect of the spatially averaged z component of the radiation force.

Depending on the manipulation process, the presence of these lateral forces can be detrimental to performance and may cause particles to form large aggregates which may sediment out of the suspension or block and disrupt the movement of the fluid. However, some recent devices have demonstrated that lateral forces can be used to advantage by influencing the movement and trapping of particles [2,3].

2. Enclosure modes within separator device

The presence of lateral radiation forces are investigated for a micro-engineered particle separator. This device relies on the movement of particles to a nodal plane under the influence of axial (y) radiation forces, then allowing particle clarified flow to be drawn off one side of the particle stream. The device has a layered structure and includes a silicon matching layer, a fluid layer and a Pyrex reflector layer [4]. The layer thickness y dimensions are relatively small compared to the length and width (x and z dimensions), therefore, when driving the device at frequencies which excite a thickness resonance the acoustic characteristics through the y-axis should predominate. Fig. 2 illustrates the basic construction and operation of the device, and orientation of the axial y and lateral z axes.

Lateral variations within the device can be caused by structural modes within the chamber walls, near-field effects or enclosure modes. Here, enclosure modes, which may be excited together with the axial modes required for operation, are investigated in isolation. The expression below describes the enclosures modes for a rectangular cavity with either rigid or pressure release boundaries [5]:

$$f = \frac{c}{2}\sqrt{\left\langle \frac{l}{L_x} \right\rangle^2 + \left\langle \frac{m}{L_y} \right\rangle^2 + \left\langle \frac{n}{L_z} \right\rangle^2}, \qquad (1)$$

where the various dimensions of the waveguide are given by L_x, L_y and L_z with relative mode orders of l, m and n. The existence of such modes within the separator device will give rise to lateral (z) as well as axial (y) pressure gradients and, therefore, components of acoustic force acting in both these directions. Whilst the mode shape and resonant frequency in a simple rectangular cavity can be determined analytically (Eq. (1)), the geometry and therefore the

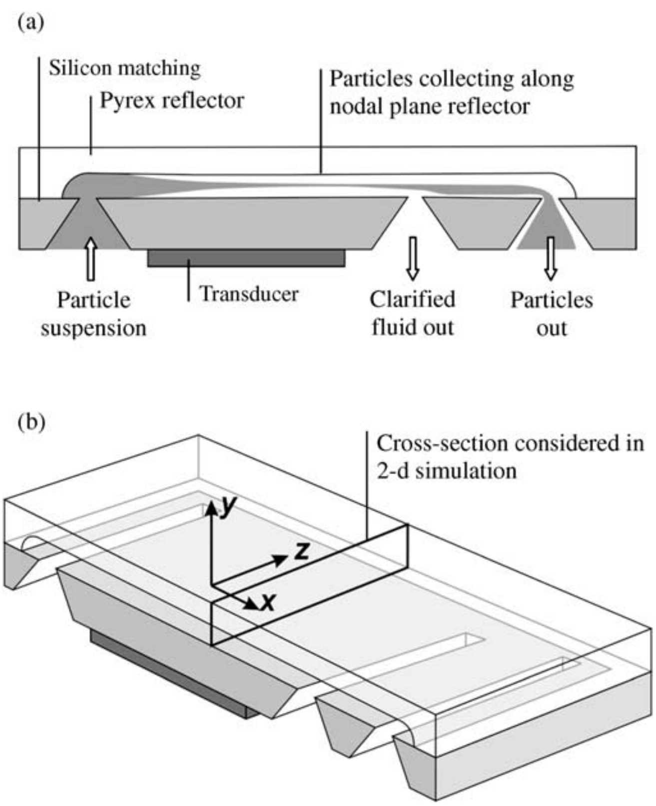

Fig. 2. Schematics of particle separator showing (a) movement of particles through the device and (b) orientation of axial (y) and lateral (z) components.