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A Novel Binary Particle Fractionation Technique

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Abstract

An interesting development towards a robust particle fractionator is presented. Typically acoustic fractionators rely on time of flight in a constant acoustic field to separate different populations[1,2]. Such a system requires all particles to be concentrated to an initial known point before entering the acoustic field. As the particle population enters the acoustic field, the particles will move towards the nodal point at velocities dictated by their relative size. If the size of the acoustic chamber, flow rates and radiation forces are carefully adjusted, particles can be graded across the width of the chamber when they exit the acoustic field.
In this work we describe a technique that allows a more robust fractionation technique which is less sensitive to residence time and allows particle populations to be split in a binary fashion. Modelling results and initial experimental results are presented.

Keywords: fractionation; standing waves; ultrasonic separation

1. Introduction

Fractionation of populations of particles by their size is a subject that is receiving increasing interest. Fractionation can be used to filter or refine samples as well as allowing certain components eg groups of cells to be separated from single cells. Acoustic fields can be used to fractionate populations and typically rely on differences in time of flight of a given size of particle to effect separation but this can result in systems that are very sensitive to flow rates and field strength.

Radiation forces on a particle in a fluid can be described by equation 1 which is an expression for the time-averaged acoustic radiation force on a compressible spherical particle of radius a, at position x within a one dimensional standing wave of acoustic energy density ε.

$$F(x) = 4\pi k \varepsilon a^3 \Phi(\beta, \rho) \sin(2kx) \tag{1}$$

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Where k is the wave number and $\Phi(\beta,\rho)$ is the acoustic contrast factor, defined as in equation 2

$$\Phi(\beta,\rho) = \frac{\rho_p + \frac{2}{3}\left(\rho_p - \rho_f\right)}{2\rho_p + \rho_f} - \frac{\beta_p}{3\beta_f} \tag{2}$$

where β and ρ are the compressibility and the mass density of the fluid and the particle, indicated by subscripts f and p respectively. The wave number, k is equal to $2\pi/\lambda$ where λ is the wavelength and the compressibility is related to the speed of sound, c, by

$$\beta = 1/\rho c^2 .$$

Inspection of this equation shows that the force experienced by a particle varies as radius cubed, and that the magnitude of the force varies with x. It can be shown that the equilibrium position for particles of the same material in an acoustic field balanced against gravity is the same irrespective of particle size, subject to the constraint that the particle is small compared with the wavelength, so all particles, large and small will eventually arrive at the same point. However, the time needed to reach equilibrium is dependent on the size of the particles as, for a given particle material, different sized particles will experience different forces. Larger particles experience larger forces. However, once a particle starts to move, it will also be affected by drag forces, which are also dependent on the size of the particle. Smaller particles will have lower terminal velocities than larger ones, so a differential velocity is created, leading to a different time of arrival. This effect has been exploited by [2] to demonstrate a fractionator, but because eventually all particles will end up in the same place, this technique is very sensitive to residence time in the acoustic field. To long a residence time and all the particles end up in the same place, but too short a time and they don't separate efficiently.

One potential way of reducing the constraints of this multiple balance is to use frequency switching to reduce the constraint of residence time. In the system described above, an excess dwell time in the acoustic field results in all particles moving to the nodal point. By electronically switching frequencies at a controlled rate, there is no longer a constraint on maximum dwell time. A feature of such a technique is that it no longer allows a continuous grading of the particle sizes across the width of the device, but rather the population is split into 2 fractions, with the split point (in terms of size) being dictated by the frequency switching rate (easily controlled electronically). Such a principle has been demonstrated by Petersson [3], although the technique described here is subtly different from Petersson's technique and will result in relatively narrow bands of particles with clear spatial separation between populations, as once the larger particles have been moved to position, they will tend to move between different nodal planes from the smaller particles. In any technique involving differential time of flight to separate populations, it is necessary to have the whole population starting from the same point. This requires some form of prefocussing prior to separation. In the case demonstrated by Kumar [2], hydrodynamic focussing was used to concentrate the population at the side of the chamber. This is not ideal as it places particles in an area of low flow velocity, and also introduces extra fluid into the system, thus reducing concentration. The mode switching technique allows the use of prefocussing to the centre of the channel, which can either be achieved hydrodynamically again, or by another ultrasonic step using a half wave resonator to move the particle population to the centre of the channel.

The principle is illustrated below in figures 1 and 2. A chamber with two transducers is used. The first transducer allows all particles to be concentrated into the centre of the chamber, so everything starts from a known point. This is illustrated in figure 1 which shows the first chamber operating continuously at a frequency to force all particles to the centre.

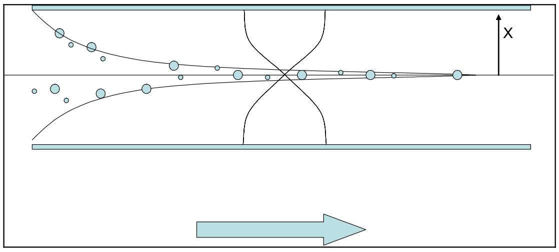
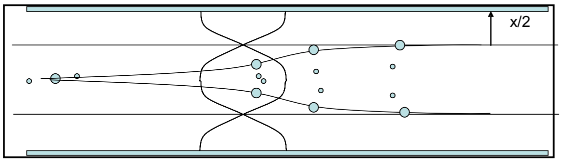


Fig.1 Transducer 1 concentrates everything (frequency f).

The second transducer then applies a switch between two modes to provide the separating mechanism. In this case we are using frequencies of f, 2f and 3f. The effective result of this is that the centre node is periodically removed where two outer modes are maintained. Thus larger particles that move faster will reach the outer nodes whereas smaller particles are pulled back to the centre. In this way the particle population is broken into two discrete populations (large and small) with the small particles are constrained to the centre node, and the larger particles are moved to the two outer nodes. In principle, a third chamber could then be used operating at 3f, to tighten the density of the concentration in all three modes, making tapping the flow off easier. By altering the duty cycle between these two modes, it is possible to tune the device electrically to adjust the particle cut off size.



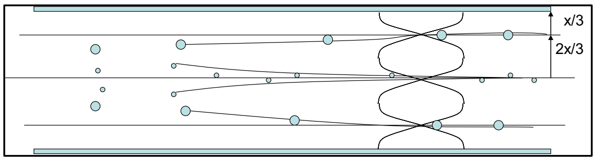


Fig.2a Transducer 2 switches between 2f and 3f (2f shown)

Fig.2b Transducer 2 operating at 3f

2. Modelling

In order to design an efficient multilayer device capable of supporting three suitable modes, some modelling was carried out. To provide an estimate of a starting point, an indicative solution can be found by considering a two layer system [5]. Here a fluid layer with a rigid boundary coupled to a reflector layer with a pressure release boundary is considered, and this leads to equation 3.

$$k_f t_f = \tan^{-1}\left(\frac{r_f\left(r_r^{\,2} + r_0^{\,2}\tan^2\left(k_r t_r\right)\right)}{r_r\tan\left(k_r t_r\right)\left(r_r^{\,2} - r_0^{\,2}\right)}\right) \qquad (3)$$

where tr and tf are the thicknesses of the reflector and fluid layers respectively, k is the wave number and rf and r0 are the acoustic impedances of the fluid and reflector layers. This equation is shown graphically in figure 3, which can be used to establish a trial solution. A straight line passing through (0,0) indicates a fixed structure, and the required solution requires a line that crosses the solutions at a Y co-ordinate of 0.5, 1 and 1.5, as this gives a half, a one, and a 1.5 wavelength solution in the fluid layer. A suitable line is indicated in figure 3, indicating that a solution is achievable.

This trial solution was refined within a Matlab model for a multilayer structure using brass as the carrier layer and glass as the reflector layer which gave a target geometry as shown in figure 4, where tx denotes a bonded PZT transducer.

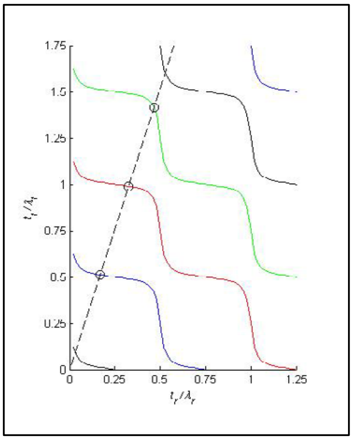


Fig.3 Graphical solutions of equation 3

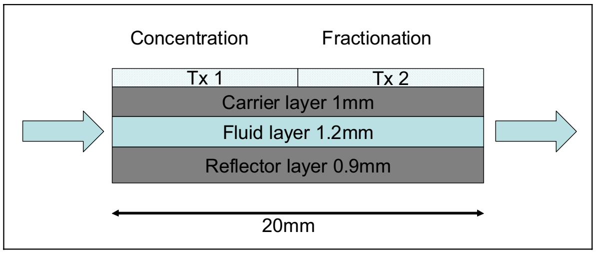


Fig.4 Layer thicknesses of the final solution

The predicted pressure profiles for such a structure were created as shown in figure 5.

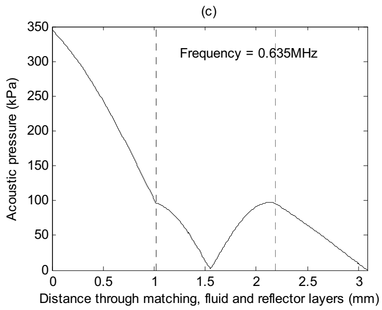


Fig.5a Mode 1 f=0.635MHz

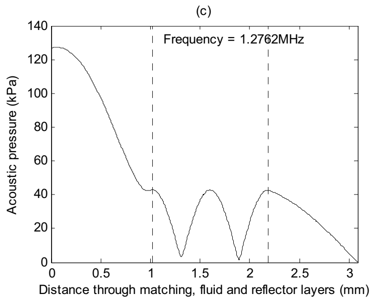


Fig.5b Mode 2 f=1.276MHz

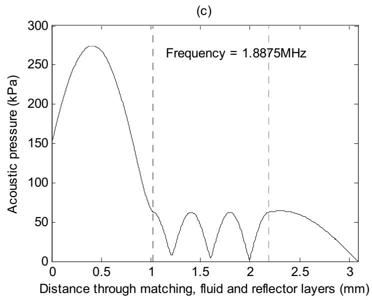


Fig.5c Mode 3 f=1.88MHz

3. Construction

An initial device was constructed from brass with a glass reflector layer to allow visibility into the device. As this was a device modified from another project it was not suitable for demonstrating separation, but allowed good access so that what was happening in the channel could be visualised easily by viewing vertically down the single outlet. The resonances of the device were established to be at 660kHz, 1.31MHz and 1.926MHz, in good agreement with the model.

Testing with 10um latex particles was carried out to confirm the activity of the modes. The driving frequency was adjusted to match the resonances of the device, and images from the outlet are given in figure 6.

Mode 1 shows the half wave mode, suitable for the prefocussing step, whereas modes 2 and 3 illustrate the two fractionation modes, with mode 2 having two nodes, and mode 3 clearly showing the three nodes.

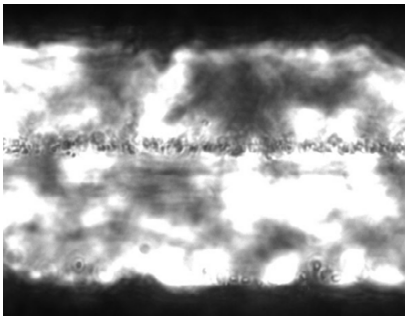


Fig.6a Mode 1 660kHz

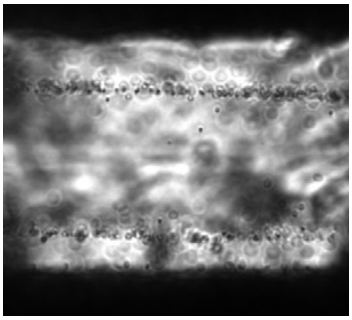


Fig.6b Mode 2 1.31MHz

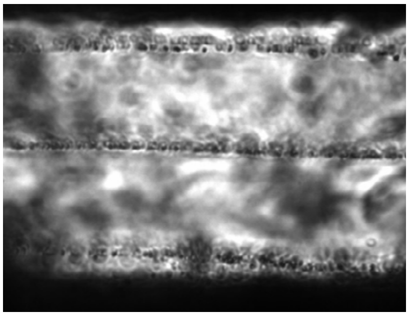


Fig.6c Mode 3 1.926MHz

4. Conclusion

The principle of a novel binary fractionation technique has been described and modelled, and the potential to build a device with suitable characteristics has been verified. Future work is planned to produce a design of system suitable for demonstrating fractionation based on the results presented here.

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