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Two dimensional manipulation of micro particles by acoustic radiation pressure in a heptagon cell

A.L. Bernassau¹, C.-K. Ong³, Y. Ma¹, P.G.A. MacPherson, C.R.P. Courtney³, M. Riehle², B.W. Drinkwater³ and D. R. S. Cumming¹

¹ School of Engineering, University of Glasgow, Glasgow, G12 8LT, UK
² Centre for Cell Engineering, Institute of Molecular, Cell and Systems Biology, College of Medical, Veterinary and Life Sciences, University of Glasgow, Glasgow, UK
³ Department of Mechanical Engineering, University of Bristol, Bristol, BS8 1TR, UK

Abstract—An acoustic particle manipulation system is presented, using a flexible printed circuit board formed into a regular heptagon. It is operated at 4 MHz and has a side dimension of 10 mm. The heptagonal geometry was selected for its asymmetry which tends to reduce standing wave behaviour. This leads to the ability to gain fine control of the acoustic field by varying the output phases of the transducer elements. Configurations with two and three active transducers are demonstrated experimentally. It is shown that with two transducers the particles align along straight lines, the position of which can be moved by varying the relative excitation phases of the two transducers. With three active transducers, hexagonal shaped patterns are obtained that can also be moved, again according to the phase of the excitation signals. Huygens principle based simulations were used to investigate the resultant pressure distributions. Good agreement was achieved between these simulations and both Schlieren imaging and particle manipulation observations.

Index Terms—sonotweezers, acoustic radiation pressure, flex circuit, heptagon cell, microfluidic system, particle control, particle trapping, 2D manipulations.
I. INTRODUCTION

Techniques that allow the manipulation of cells and micro particles by non-invasive means are desired to facilitate biological applications such as microarrays [1] and tissue engineering [2]. Non-invasive techniques exploiting the acoustic radiation force have been demonstrated for trapping, separating [3] and rotating particles [4].

Most of the devices reported are based on acoustic standing waves and hence they generate fixed patterns of acoustic pressure nodes/antinodes. It is at these nodes of pressure that dense particles under manipulation agglomerate.

Is has been shown how one transducer and a reflector can be used to create a standing wave that trap particles. With this technology, it was possible to trap particles and transport them by changing the driving frequency [5, 6]. This method presents several challenges such as an unstable force resulting in movement among trapped particles. An alternative method is to form interference patterns using travelling acoustic waves. Courtney et al [7] describe a device in which acoustically matched transducers are used in opposed pairs. This arrangement means that sound emitted by a given transducer is absorbed by its opposing transducer meaning that each transducer element can be thought of as emitting travelling waves into a large volume. Multiple transducers can then be used to form standing waves which can be controlled by varying the relative output phase.

It has also been shown that transducers immersed in a large (effectively infinite) water tank may be set at angles and used to create complex interference patterns [8, 9]. In this case, the tank is so large that reflections are negligibly small. However, whilst suitable for demonstrating acoustic phenomena without interference due to the reflections, a large water tank is not appropriate for many applications. A more convenient device for bench-top biological experiments will require a suitable test cell that is geometrically constrained. This paper demonstrates a method of applying the multi-transducer approach in a limited space, by relying on multiple reflections to get rid of the energy. We also demonstrate two dimensional particle manipulation for a microfluidic scale cell, with transducers operating at 4 MHz using various geometries in a closed system. The acoustic force responsible for the trapping is formed by standing waves generated by activating two or three transducers at angles whereby the acoustic beams from the transducers cross within the chamber. The structure of these devices, termed sonotweezers, and their principle of operation are discussed. Furthermore, characterisation of the acoustic beam patterns and particle manipulation capabilities are described.

II. STRUCTURE AND PRINCIPLE

The sonotweezer is made by bonding plates of NCE51 Noliac Ceramic lead zirconate titanate (PZT) (E.P. Electronic Components Limited, UK) to a flexible printed circuit board, or ‘flex circuit’ (Flexible dynamics Ltd, UK) and forming it into a heptagon.

As shown in Fig. 1, the heptagonal flex circuit is first sandwiched between two Plexiglas plates to create a sealed unit. Secondly, this sealed heptagon is then mounted on a rigid PCB to allow simple connection to each transducer element.
The PZT plates were 5 mm x 5 mm with a thickness of 0.5 mm. The flex circuit was a ribbon of 10 mm width and 95 mm in length, each face of the heptagon was 10 mm long.

The seven transducers have a common ground and were each driven using a 4 MHz sine wave of $V_{pp} = 8$ V. Synchronisation between channels was achieved using two arbitrary waveform generators providing four output each (TGA12104, Aim and Thurlby Thandar Instruments, UK) allowing independent control of the amplitude, phase and frequency. The signals from the waveform generators were amplified by high speed buffer, BUF634T (Texas Instruments, UK).

The system is controlled by a virtual control panel developed in Labview (National Instruments, UK). The Labview interface allows real time voltage, frequency and phase control.

The main advantage of using flex circuit material is to allow the easy assembly of a variety of device. The heptagon shape explored in this paper was chosen to minimise the build-up of standing waves, a phenomenon that is most likely to occur in a devices with parallel sides. For example, Fig. 2 shows what happens when two unmatched transducers are positioned parallel to one another (i.e. in opposition). The photograph shows particles trapped along the acoustic pressure nodes as expected. Crucially the standing wave pattern is unaffected by the phase of the driving sine wave(s) and so this configuration can trap particles but it cannot manipulate them.

Fig. 1 Device shaped into a heptagon and bonded to a PCB to ease the connection of each channel (cell size ~ 2 cm).

Fig. 2 Photograph of trapped particles when two transducers are opposed to each other (sketch in inset) but only one transducer is excited (indicated by a thick solid line in the inset).
The heptagon shaped cell was investigated with two and three transducers simultaneously excited by continuous sine waves. Fig. 3 shows the different combinations investigated in the case of two transducers. Fig. 4 shows the two configurations with three excited transducers and resulting crossed acoustic beams.

![Fig. 3 Different combinations investigated for 2 transducers.](image1)

![Fig. 4 Two configuration 1-4-5 and 1-3-5 of the excited transducers and the resulting crossed acoustic beam.](image2)

To better understand the reflections occurring in a closed cell, a ray model can be used to predict the path of the acoustic waves and the reflections occurring within the heptagon shaped cell. Fig. 5 shows the path of two possible rays generated by one active transducer. After 3 reflections, the wave hits another face at 90 ° and subsequently follows the same path again, although in the reverse direction. Therefore, the reflected path length is approximately 3 times that of a parallel sided device. This increased reflected path means that the reflected signals are relatively weak compared to the initial transmission. In turn this means that travelling wave effects dominate over standing wave effects, as is later demonstrated.
Fig. 5 Reflections present in the cavity when one transducer is excited.

A Huygens’ model based on Huygens principle was used to simulate the acoustic pressure distribution within the chamber with one or more active transducers. To make the model as simple as possible it was assumed that the boundary was perfectly absorbing, i.e. reflections were negligible. The wave field generated by a given transducer, \( g(r) \) was then modelled as the sum of a number of simple cylindrical point sources, \( f(r) \) as,

\[
f(r) = Ae^{-\frac{\alpha r}{\lambda}} \cos(\omega r - kr + \phi)
\]

(1)

\[
g(r) = \sum_{i=1}^{N} f(r_i)
\]

(2)

where \( A \) is the amplitude, \( \alpha \) is the damping factor, \( \lambda \) the wavelength and \( \phi \) the initial phase in degrees.

If \( M \) is the point where the function is computed, in the case of infinite planar waves, \( r \) is the distance of \( M \) to the line on which the transducer is situated. In the case of spherical waves, \( r_i \) is the distance of current point \( M \) to transducer \( i \) (Fig. 6). The actual, finite size transducer is then simulated as several (e.g. 10) sources uniformly distributed over the region of the active transducer. These waves are then summed at a particular region in space to simulate the transducer output. Additional transducers can be included and the results summed to simulate the effect of exciting multiple transducers. For example, Fig. 7 shows results of a simulation where ten spherical acoustic waves were used for each excited transducer.

Fig. 6 Drawing showing point sources located next to each other and spanning the actual transducer. The wave at any position, \( M \), is calculated from the sum of waves from the point sources.
The simulation shown in Fig. 7 indicated that, as expected, nodes and anti nodes are formed in a distinct pattern. All physical parameters of frequency, amplitude, and phase can be varied to investigate the effect of these variations on the distribution and pattern of the energy minima.

Fig. 7 Nodes and antinodes created by three excited transducers in the case of (a) the configuration 1-4-5 and (b) the configuration 1-3-5.

III. RESULTS AND DISCUSSION

A. Characterisation

Each transducer was characterised by a network analyser (E5071B, Agilent, UK) to extract impedance magnitude and phase characteristics. The resonance frequency of the transducers was found to be 4.25 MHz. The impedance magnitude of each transducer was approximately 40 Ω around 4 MHz. This impedance magnitude is close enough to 50 Ω so no impedance matching was necessary.
The acoustic beam pattern was characterised by a Schlieren optical system [10, 11], which is shown schematically in Fig. 8. The system uses an LED as a point source of light to produce uniform illumination. A condenser and an adjustable slit were used to cut off most of the light to the sides, resulting in a vertically oriented line-like light source. The condenser was chosen to have a larger f-number than the converging lenses and this ensured that the converging lens was fully illuminated. Two converging lenses are used to collimate the light. The collimated light then passes through the active heptagon device. Direct light is blocked by placing a knife edge at the focus point. The knife edge has been mounted onto a three axis stage to allow a good control in the parallelism between the knife edge and the slit and perpendicular to the propagation of ultrasound.

![Schlieren imaging set up used for characterising the acoustic beam pattern.](image)

Fig. 8 Schlieren imaging set up used for characterising the acoustic beam pattern.

The three transducers were excited at a frequency of 4 MHz with a voltage of 8 V_{pp} simultaneously creating standing waves in the region where the acoustic beams crossed. At this frequency, the wavelength of the sound waves in water was \( \lambda = 0.375 \text{ mm} \). Fig. 9 shows a photograph of the acoustic beam pattern in water with the device for configuration 1-4-5 and configuration 1-3-5. It could be observed that the position of the pressure nodes/antinodes can be shifted as a function of the relative phases of the transducers. The Schlieren images match very well the simulation data (Fig. 7).

![Schlieren image of the acoustic beam pattern in (a) configuration 1-4-5 and (b) configuration 1-3-5.](image)

Fig. 9 Schlieren image of the acoustic beam pattern in (a) configuration 1-4-5 and (b) configuration 1-3-5.

**B. Particle trapping and manipulation**

All particle trapping experiments were performed using 10 \( \mu \text{m} \) diameter polystyrene beads (Polysciences Europe, Germany). The transducers were excited with 8 V_{pp} with a frequency around 4 MHz. In all experiments particles were trapped by exciting either two
or three transducers simultaneously and the position of the particles controlled by shifting the phase of one of the transducers relative to the others.

Two transducers

When two transducers are simultaneously excited (Fig. 3), the particles align along a line that bisects the angle formed by the two cell sides on which the transducers are affixed. The distance $d$ between the nodes can be calculated by $d = \frac{\lambda}{2} \sin(\theta/2)$ with $\theta$ the angle formed by the normals to the planes of the two sides with the active transducers. In the cases studied here, $\theta$ equals $51^\circ$, $105^\circ$ and $154^\circ$ for the combination 1-2, 1-3 and 1-4 respectively (Fig. 3).

In combination 1-2, the particles aligned along lines separated by the theoretical distance of $440 \, \mu m$, there is particle movement visible, probably due to streaming effects. Fig. 10 shows a photograph of the aligned particles. This poor trapping is probably the result of the geometry of the transducers. With a separation angle of $51^\circ$ degrees, not all the energy is transferred into the direction of the standing waves. For two transducers, an interference pattern is created between the two travelling waves from each one. The standing wave vector is parallel to the line that bisects the normal to the plane of each transducer. However, not all the acoustic power is transferred into the standing wave, and a proportion from each one continues to propagate along the normal. This gives rise to streaming motion outside the area where interference occurs.

![Photograph of aligned particles for the combination 1-2.](image)

Figure 11 shows the results from combination 1-3, when two transducers separated by one inactive transducer are simultaneously excited. The particles align along the lines visible in Fig. 11 and travel along these lines under the acoustic energy emanating from the transducers. The lines have a separation of $236 \, \mu m$. Fig. 11b shows the effect of increasing the phase of transducer 1; the particles move towards transducer 3. It should be noted that the phase shift moves the particles by $d/4$, $59 \, \mu m$ for each $90^\circ$ step. With the same combination, if the phase is increased in transducer 3, the particles move towards transducer 1.
In combination 1-4, when two transducers are separated by two inactive transducers, and are simultaneously excited, the particles align at the nodes with a separation of 192 µm. Fig. 12a show the beads aligned. In this combination, when increasing the phase of transducer 4, the particles move towards the left, towards transducer 1. Fig. 12b shows an overlay of pictures illustrating the particles movement when changing the phase from 0° to 270° of transducer 4 with a step of 90°. It should be noted that the phase shift make them move by \( d/4 \), 48 µm for each 90° step. With the same combination, if the phase is increased in transducer 1, the particles will move in the right, towards transducer 4.

By using smaller phase shifts of 20°, the displacement of the lines along which particles align can be plotted against phase change when the combination of transducer 1 and 4 were excited, and the phase of one transducer is shifted against that the other (Fig. 13). The displacement was measured using a fixed reference graticule in the image analysis software (ImageJ). The plot shows near linear correlation between the line displacement and the relative phases of the transducers as expected by simple theory.

![Graph showing displacement vs. phase change](image)

**Fig. 13** Particles displacement versus phase change between transducer 1 and transducer 3: measurements (○) and prediction (solid line) (n=5).

**Three transducers**

Fig. 14a and e shows photographs of the beads agglomerating when three transducers were active in phase and in configurations 1-4-5 and 1-3-5, respectively.

In configuration 1-4-5, the particles cluster around the antinodes, forming a deformed hexagon with two longer sides (Fig. 14a). Because of previous observations with 2 transducers in combination 1-2, 1-3, and 1-4, it was expected that configuration 1-3-5 would be more effective in trapping, and indeed, Fig. 14c shows the particles clustering along a clear hexagonal pattern.

When the phase of one of the three transducers is shifted, the nodes and antinodes changed position, moving the position of the clustered particles with them. Fig. 14b and d show the overlay of two photographs of the respective particle pattern when the phase of the transducer 1, 4 and 5 had been shifted by 180° respectively. The hexagon shape has been redrawn on top of the agglomerated
particles to facilitate the visualisation of the movement of the trapped particles during shifting. The green hexagon shape represents the agglomerated particles at phase equals 0° and the red one represents the particles trapped when the phase has been shifted by 180°. It can be easily noticed that the particles can be moved in a predictable manner in two dimensions and at the same time retain their relative position, simply by shifting the phase of one of the three transducers.

Similar data has been demonstrated for the configuration 1-3-5.

The photographs have been taken where particles clusters in the middle of the cavity. Fig. 15 shows the particle trapped and clustered depending on their position within the heptagon cavity. The best clustering naturally occurs in the middle of the cavity where the 3 beams cross.

Fig. 11 (a) Photograph showing the trapped particles with combination 1-3 (b) Picture of the overlay of four photographs taken at four different relative phase shifts of transducer 1 and transducer 3 (red = 0 °, green = 90 °, blue = 180 ° and pink = 270 °) showing the movement of the particles.

Fig. 12 (a) Photographs showing the trapped particles with the transducers 1-4 (b) Picture of the overlay of four photographs taken at four different relative phase shifts of transducer 4 and transducer 1 (red = 0 °, green = 90 °, blue = 180 ° and pink = 270 °) showing the displacement of the particles.
Fig. 14 Photograph of clustered particles for (a) configuration 1-4-5 and (c) configuration 1-3-5. Picture of the overlay of two photographs with two different phase shift (pink = 0 ° and other colour = 180 °) showing the movement of the particles for the configuration 1-4-5 with (b) the transducer 1, the transducer 4, the transducer 5 and for the configuration 1-3-5 with (d) the transducer 1, transducer 3 and transducer 5.

Fig. 15 Comparison between experimental photograph (left) and simulation (right) for configuration 1-4-5 and 1-3-5 of trapped particle.

IV. CONCLUSION

A simple and highly versatile fabrication process, involving PZT plates bonded to a flex circuit, has been developed and its application to acoustic manipulation of particles in 2-D demonstrated. The flex circuit allows easy shaping of the device and various geometric configurations of the active elements can be achieved. Here we demonstrate the properties of a heptagon arrangement that was chosen to avoid direct reflections and hence minimise standing waves. Other geometries, including asymmetric designs to further reduce standing wave behaviour, could be created using the same approach.
A Huygens based model that assumes absorbing boundary conditions (i.e. neglects reflections) was used to predict the resultant acoustic field patterns in the device. Good agreement between the model and both Schlieren photography of the pressure field and observed distribution of 10\(\mu\)m diameter polystyrene beads was achieved, suggesting that the assumption of absorbing boundary was reasonable.

The case of two excited transducers resulted in the trapping of particles along lines perpendicular to the bisection of the transducer normals. The combination where the activated transducers were on adjacent sides of the device was shown to be less effective in trapping than the combination where at least one inactive face separates the active transducers. Adjustment of the relative phase difference between the active transducers allowed controlled movement of the lines of particles and this was particularly effective when the active transducers where the transducers are not adjacent.

When three transducers were excited a number of more complex pressure and particle distributions were observed. The one involving excited transducers separated at least by one cell side (Fig 14c) was shown to be superior to the one in which two of the excited transducers were adjacent (Fig 14a). For both configurations adjustment of the relative phase resulted in controlled movement in two-dimensions of the particles and acoustic pressure distribution.

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REFERENCE


