The performance of an acoustic levitator

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Abstract. An acoustic levitator uses an array of ultrasonic transducers to generate a standing acoustic pressure field which exerts a radiation force on small particles, allowing the particles to be trapped, relocated, separated or combined. Experiments on levitating particles of different densities and calculations of the acoustic radiation force and moment have been reported in the literature. However, direct inspection on the acoustic pressure field pattern is seldom carried out. This paper reports an investigation on the performance of an existing acoustic levitator design, which uses off-the-shelf components, by comparing the visualized pressure field from Schlieren imaging to analytical simulations. The ability to compare Schlieren imaging results to analytical simulations readily can prove to be a vital tool. Since the simulations provide an ideal pressure field, the imaging of the levitator pressure field can highlight discrepancies between the real and ideal cases. This can be especially useful as a diagnostic tool to identify the cause of a drop in performance of the acoustic levitator in a real world scenario.

1. Introduction

Acoustic levitation utilizes steady acoustic radiation force [1] to trap particles in the mid-air. The acoustic radiation force is comprised of monopole scattering factor, which is resulted from the contrast between the volume change of the particle and the surrounding fluid due to the acoustic pressure, and dipole scattering factor, which is the relative difference in inertia between the particle and surrounding environment. This inherent property of acoustic levitation is able to provide advantages over other kinds of levitation mechanism. For example, optical trapping [2] requires the materials to be dielectric or optically transparent. In addition, the size of levitated particle is limited to micron-scale. Magnetic levitation [3], on the other hand, is capable of holding heavier and larger samples, but is also restricted to ferromagnetic materials. However, using acoustic levitation, particles of different materials, ranging from liquid droplets to electronic components, can be levitated. The existing design [5] also shows the ability to trap a wide range of sizes of millimeter scale.

A wide range of acoustic levitation designs [4-9] have been demonstrated in previous studies. Single-sided planar levitator design using dozens of coupled emitters and reflectors to form a 1-dimensional...
array for horizontal manipulation of particles was reported in [4]. Single-axis levitator designs consisting of two transducers at two ends [5] or one transducer and one reflector at each end [6, 8] to produce ultrasound standing waves [5–6, 8] is also a kind of common configuration. Furthermore, some configurations expanding standing wave field to three-dimensional structure, such as by forcing two sound beam axes to cross in an angle [9] or by using concave inward-circular arrays of transducers [7], have also demonstrated great potential for many applications.

There have been a few applications of acoustic levitator in biotechnology and chemistry studies, such as contactless DNA transfection by using an optimized Langevin piezoelectric transducer (LPT) as a resonator and a flat reflector to transport transfected cells [8], amorphous drug development with the help of containerless processing techniques [10], monitoring and in situ diagnosis of malaria in a remote environment by coupling an acoustic levitation device with a portable Raman spectrometer [11] and holding samples, such as aspirin and vitamin C, for crystallization process inspection by using synchrotron diffraction [12].

In most of the studies on the design or application of acoustic levitation, the performance of the acoustic levitators was evaluated by numerical simulation instead of direct inspection. In this study, we demonstrate a method to directly visualize the acoustic field within an acoustic levitator. The acoustic levitator is based on the “BigLev” design reported in [5] and the pressure field within the acoustic levitator is visualized using Schlieren imaging. Quantitative data is extracted by using image processing techniques and is compared to data from analytical simulations which represents the ideal pressure field. The method has the potential to help in the quick identification of discrepancies or changes in performance of a physical acoustic levitator through a direct inspection method.

2. Experimental Implementation

2.1. The design of Acoustic Levitator

A multi-emitter single-axis acoustic levitator [5] was chosen to demonstrate our approach to evaluate the performance of an acoustic levitator. The levitator in figure 1 is comprised of two sets of transducers as signal emitters, which only required low voltage (ca. 20V) compared to other current levitators (>100V). The components are easily accessible, and the construction of the device is based on 3D printing. In a departure from the original design [5], we use 72 transducers operating at 40 kHz, 36 on each side, with larger diameter and higher power for our investigation.
Figure 1. The acoustic levitator (“BigLev”) with 36 transducers (diameter 16mm) on each side, an electronic driving circuit, which consists of an Arduino Nano micro-controller, a L298N motor driver, and a cooling DC fan.

2.2. Fundamentals of Light Propagation Through an Object with Inhomogeneous Density Field

Schlieren visualization method was used to experimentally capture the pattern of pressure field generated by the acoustic levitator. The Schlieren imaging system provides a direct inspection into the operating performance in a real world scenario. The experiment results are also used for comparison with the ideal case.

To get a full insight into the mechanism involved in generating Schlieren image, how the light beams will respond after propagating through the inhomogeneous density field is explained first. In figure 2 [13], a density difference exists along the z-axis, which leads to the refraction index $\frac{\partial n}{\partial z} \neq 0$. By examining figure 2 [13], the following is obtained:

$$\frac{\partial^2 z}{\partial y^2} = \frac{1}{n} \frac{\partial n}{\partial z}$$ (2.1)

also, the simple relationship between the refractive index and field density $\rho$ is given by

$$n-l = k\rho$$ (2.2)

where $k$ is known as Gladstone-Dale coefficient, which is nearly constant over most of the visible spectrum. In figure 3, the deflection angle can also be derived and expanded to planar coordinate:

$$\varepsilon_z = \frac{1}{n} \int \frac{\partial n}{\partial z} \partial y$$

$$\varepsilon_x = \frac{1}{n} \int \frac{\partial n}{\partial x} \partial y$$ (2.3)

In figure 3, because of the small deflection angle, the displacement on any planes perpendicular to propagation direction can be obtained by multiplying the deflection angle with the travel distance $l$ of the light beam to get [14]

$$(QQ')_x = l \frac{1}{n} \int \frac{\partial n}{\partial x} \partial y$$

$$(QQ')_z = l \frac{1}{n} \int \frac{\partial n}{\partial z} \partial y$$ (2.4)
**Figure 2.** Diagram of light-ray deflected by a refractive-index gradient by $\partial n/\partial z$ [13].

**Figure 3.** Displacement of a light ray on the recording device after passing through density field [14].

These equations relate the amount of displacement to refraction index gradient, which can differentiate inhomogeneous parts from the testing object. Schlieren imaging system applies this mechanism to visualize inhomogeneous density field, such as, in our case, the acoustic pressure field.

2.3. **Set-up**

This section describes the approach to construct a Z-shape Schlieren imaging system.

A Z-shape Schlieren imaging system is built (see figure 4 [16] and figure 5) using off-the-shelf components. The system consists of two 160mm diameter, 1300mm focal length parabolic mirrors, a mounted blue LED, an LED driver, a plate with a pinhole in front of the light source to prevent dispersive light in the final image, a razor blade fixed on a stand, a linear stage for the blade stand, and a Canon EOS 80D DSLR camera equipped with a f/2.8 fast lens.

![Figure 4. [16] The scheme of Schlieren imaging system.](image-url)
Figure 5. The final set-up of the Schlieren imaging system. Light from the light source reflects off the first mirror to pass through the levitator and towards the second mirror (not shown in image). After reflecting from the second mirror, light which is not blocked by the razor blade reaches the camera.

An LED driver is added to protect the light source from voltage or current fluctuations (which cause the output to vary and degrade) and stabilize the system to produce consistent results. The cap is placed to create a point light source and block off dispersive light, which will cause diffuse glow in the image.

2.3.1. Alignment
The first step is to place two mirrors and light source on a single axis. The two mirrors are placed at least 2f apart to prevent optical issues, such as double image, and the light source is placed at the focal length of the first mirror to generate collimated light projected on the second mirror. Once these are aligned, the occlusion of the LED light source by components that are part of the Schlieren setup but not within the region of collimated light between the mirrors can be seen in the projected image (see figure 7 (a)). The mirrors and light source can be moved carefully outward to the final Z-configuration until the occlusion completely disappears. In each iterative move, the light beam projected on the second mirror should be the same size as the mirror and cover it completely (see figure 6 and figure 7 (b)). Next, the razor blade is positioned at the focal length of the second mirror with the focused light at the edge of the blade to allow any light deflected due to a change in refractive index to bypass the blade. Finally, the camera is adjusted to face the expanding cone of light beyond the razor blade.

Figure 6. The projection of the light source on the second mirror after reflection from the first mirror. (a) Light source too close to the first mirror, (b) Light source too far from the first mirror, (c) Light or mirror are not aligned with the central axis, (d) ideal.
Figure 7. The fine tuning of the Schlieren imaging system. (a) Occlusion due to components outside the region of collimated light between the mirrors. (b) An example of the light source placed too far from the first mirror, leading to a projection on the second mirror that is smaller than the mirror. (c) Adding a card in front of the light source that blocked all but a small amount of light passing through a pinhole prevents dispersive light, which causes a diffuse glow in the images (a) and (b). (d) Ideal result with sufficient sensitivity and correct alignment to capture ambient air flow.

2.3.2. Sensitivity

The minimum inhomogeneity in the flow field that can be captured is fixed by the sensitivity of the Schlieren imaging system.

With the help of a linear stage for planar translation, the sensitivity can be enhanced by slightly adjusting the position of knife-edge to let less light pass through, which will increase the contrast in the
image; however, the overall brightness of the image will be reduced. Formula 2.5 [14] also shows the factors that influence the change in light density:

$$\frac{\Delta I}{I} = f \frac{1}{a} \int \frac{\partial n}{\partial z} \partial y$$  \hspace{1cm} (2.5)

where $I$ is light intensity, $f$ is focal length, and $a$ is reduced length of light source image. By adding a substance with a high evaporation rate, such as alcohol (see figure 8(b)), the refractive index gradient $\partial n/\partial z$ can be increased, which increases the light intensity change and the sensitivity.

![Figure 8](image_url)

(a) (b)

**Figure 8.** Improvement in the contrast of Schlieren images by increasing the density gradient: (a) purely air, (b) with alcohol added.

### 3. Analytical simulation

Simulation is performed to obtain the ideal performance of the acoustic levitator [5]. The aim is to provide an environment to validate and evaluate the actual performance by making a comparison with the experimental results. The simulation code is written in Python based on an analytical model.

The complex acoustic pressure $P$ at point $r$ due to a source emitting at a single frequency can be modeled [5] as:

$$P(r) = P_0 V \frac{D_f}{a} \exp[i(\varphi + kd)]$$  \hspace{1cm} (3.1)

where $P_0$ is the amplitude constant that defines transducer output power, $V$ is excitation signal peak-to-peak amplitude, $D_f(\theta) = 2J_1(kasin\theta)/kasin\theta \sim sinc(kasin\theta)$ is a far field directivity function, $J_1$ is first order Bessel function of the first kind, $a$ is the radius of the piston, $\theta$ is the angle between the piston normal and $r$, $d$ is the propagation distance in free space, $k = 2\pi/\lambda$, $\lambda$ is the wavelength, $\varphi$ is the emitting phase of the source.

The total acoustic pressure ($P$) generated by $N$ transducers is the addition of the individual fields:

$$P = \sum_{j=1}^{N} P_j$$  \hspace{1cm} (3.2)

Here a more powerful levitator design is achieved by selecting transducers with 16mm in diameter that provide higher amplitude constant ($P_0$) than those in the literature [5]. Starting from creating a volumetric 3D grid (see figure 9). Two emitters, each comprised of 36 transducers, are placed at two ends. To construct a standing wave pressure, a phase difference of $\pi$ is set between the two emitters. By adding the contributions from each emitter, volumetric information of the pressure field on every grid point can be obtained. After that, a central slice, which is normal to the light propagation direction in the experiment, is extracted to compare with Schlieren imaging results.
The acoustic radiation force can also be obtained by taking the gradient of the acoustic potential. The potential is described by Gor’kov potential [5 and 15],

\[ U = 2K_1(|p|^2) - 2K_1(|p_x|^2 + |p_y|^2 + |p_z|^2) \]

\[ K_1 = \frac{1}{4} V \left( \frac{1}{c_0^2 \rho_0} - \frac{1}{c_p^2 \rho_p} \right) \]

\[ K_2 = \frac{3}{4} V \left( \frac{\rho_0 - \rho_p}{\omega^2 \rho_0 (\rho_0 + 2 \rho_p)} \right) \]

(3.3)

where \( K_1 \) and \( K_2 \) represent monopole coefficient and dipole coefficient, respectively. \( V \) is the volume of spherical particle, \( \omega \) is the angular frequency of the emitting waves, \( \rho \) is the density and \( c \) is the speed of sound (with the subscripts \( \theta \) and \( \rho \) referring to the host medium and the particle material). \( p_x \), \( p_y \), \( p_z \) represent three partial derivatives of the complex pressure \( p \).

\[ p_x(x,y,z) \approx \frac{p(x+h,y,z)-p(x-h,y,z)}{2h} \]

\[ p_y(x,y,z) \approx \frac{p(x,y+h,z)-p(x,y-h,z)}{2h} \]

\[ p_z(x,y,z) \approx \frac{p(x,y,z+h)-p(x,y,z-h)}{2h} \]

(3.4)

where \( p_x \), \( p_y \), \( p_z \) can be illustrated by the finite difference method by slightly moving the grid forward and backward by \( h \) in each direction.

Now, the acoustic radiation force can be calculated by using the negative gradient of the acoustic potential,

\[ F = -\nabla U \]

(3.5)

In figure 10, we can validate the particle is fixed by the forces pointed inward at the center.
Figure 10. (a) Acoustic potential (Gor'kov potential). (b) Acoustic radiation force. (c) Quiver plot of the acoustic radiation force. The force distribution at the centre of the pressure field is such that a particle is most likely to be trapped at this location.

4. Results and Discussions
To evaluate the performance of the existing design acoustic levitator [5], a series of processing techniques are applied on both simulation and experimental results so that comparisons can be made on the pattern of acoustic pressure along the levitation axis.

4.1. Image processing on the experimental data
The Schlieren imaging system paves a way for us to capture the picture of acoustic pressure. However, the imaging result is a combination of acoustic pressure field and medium, which is susceptible to any outside disturbance, such as turbulent airflow caused by heating of electronic devices of the acoustic levitator system. Therefore, it is necessary to utilize some image post-processing tools to extract the data out of the captured image. Here, the embedded imaging processing packages in MATLAB were employed.

4.1.1. Increase the contrast of acoustic pressure pattern
Ensemble averaging is first performed on each pixel of different frames in the recorded videos. The videos taken when power of the acoustic levitator is on and off are processed separately. The power off results are treated as the offset. The power off results are then subtracted from the power on results to remove background noise and thus to make the acoustic pressure field clearer (see figure 11(a)). By applying adapthiseq (contrast-limited adaptive histogram equalization) (see figure 11(b)), the original histogram is stretched intentionally into a more uniform distribution histogram (see figure 11(c)) in every divided segments of the picture. Therefore, the details in darker parts of the image can be seen. Moreover, the estimation of the gray level of the previous image (see figure 11(b)) can be calculated by imopen, which uses a morphological structuring element to scan through each pixel, to enhance the contrast (see figure 11(d)).
Figure 11. Results of image processing. The bright and dark lines represent acoustic pressure field, with brighter regions at higher pressure and darker regions at lower pressure: (a) background subtraction on original video frames, (b) enhancement by using `adaphiseq`, (c) changes in histograms with `adaphiseq`, (d) grayscale image through `imopen` process.

4.1.2. Calculation of centroids

The grayscale results are then turned into a binary image (see figure 12(a)) to find the locations of centroids with higher pressure values. The approach is starting by segmenting the acoustic pressure pattern into small pieces (see figure 12(b)). This is done through the construction of catchment basins (patterns of objects wanted) and watershed lines (section line) along the lines in the image (see figure 13 [17]) by `bwdist` and `watershed` function. Then, the centroids (see figure 12(c)) of them are acquired by `regionprops` function. Finally, the average locations of the centroids on the axis-direction center line are obtained (see figure 12(d)).
Figure 12. (a) binary image, (b) segments constructed through watershed method, (c) labels of centroids on each segment in (b), (d) average locations of centroids.

Figure 13. (a) Watershed and catchment basins by \textit{bwdist} and \textit{watershed} function, (b) diagram of catchment basins (darker parts) and watershed lines (brighter parts) on binary image [17].

4.2. \textit{Comparisons of simulated and experimental cases}

Here, with the simulation and experiment data placed side by side, comparison can be made to check if there are any discrepancies between the ideal and real cases.

The quantitative analysis is performed by comparing the acoustic pressure field along the central axis of the acoustic levitator with the data obtained from the Schlieren images as described in Section 4.1. The acoustic pressure is generated by the formation of standing sound wave from two side emitters. However, because the signal frequency is too high to distinguish the difference in the changes of the standing wave over a time period, the acoustic pressure field is considered to be independent of time. The locations of the peaks of the acoustic pressure field along the central axis of the acoustic levitator are extracted from the simulation data. These are the locations where any particles placed in the field are expected to be trapped. An illustration of the acoustic pressure field is shown in figure 14(a) with the pressure data extracted along the dotted line. The corresponding locations from the experiments are the centroid locations of the bright regions in the Schlieren images calculated in Section 4.1 shown in figure 14(b).
Figure 14. (a) Acoustic pressure field from simulations. The colour denotes variation in pressure and data is extracted along the dotted line. (b) Processed Schlieren image showing the varying pressure field with centroid locations of the high pressure (bright) regions plotted as symbols.

The peak pressure locations from the simulation and centroid locations from experiment are plotted in figure 15(a). From the figure, a good overlap between data from the two sources is evident at the centre of the acoustic field while away from the centre, a deviation can be seen. This deviation can be partially attributed to the quality of the Schlieren images obtained. The Schlieren image shown in Figure 11(a) is bright at the centre, while the brightness decreases towards the periphery of the image. The bright centre corresponds to a clear demarcation between the high and low pressure in figure 14(b).

The difference between the simulation and experiment data is plotted in figure 15(b). As expected, the difference is small at the centre of the acoustic field and increases away from the centre. This highlights the need for a method such as Schlieren imaging to directly visualize the acoustic pressure field. In applications where the particle trapping positions within the acoustic pressure field are to be known accurately, dependence on simulation results might prove insufficient. Further, a major deviation between the Schlieren imaging and simulation results would be indicative of a faulty acoustic levitator.
Figure 15. (a) A plot of the peak of the pressure field along the central axis of the acoustic field from simulations and the centroid locations of the high pressure (bright) regions from the Schlieren images. (b) Difference between the peak locations from simulations and the centroid locations from experiments.

5. Conclusion
A method of checking the performance of an acoustic levitator has been presented. This method is able to extend to acoustic levitators of different designs to detect different kinds of acoustic pressure patterns and further to improve the system designs to achieve better performance. The pattern of the acoustic pressure field is of importance in the precise levitating of particles or in detailed investigation on different scientific phenomena using acoustic levitation, such as crystallization and nano-assembly as any minute change in the pattern would lead to different results. Furthermore, it can also be treated as a calibration tool to help us create a benchmark that we can use to calibrate our simulations to better represent the real world environment. To be more specific, by increasing the accuracy of the simulation results, it would be possible to reduce the need for experimental trial and error and, thus, accelerate research studies involving acoustic levitators. Finally, it is hoped that this method for inspection of acoustic pressure fields will expedite the development of acoustic levitation and its applications in various fields.
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