

Planar Formation of Particles Levitated by Four Surrounding Ultrasound Phased Arrays

四台の超音波フェーズドアレイを用いた平面状粒子浮揚

Takayuki Hoshi^{1†}, Yoichi Ochiai², and Jun Rekimoto²³ (¹Nagoya Inst. Tech.; ²The Univ. of Tokyo; ³SONY CSL)

星 貴之^{1†}, 落合 陽一², 暦本 純一²³ (¹名工大, ²東大, ³SONY CSL)

1. Introduction

In our previous study [1], we developed a new method of acoustic levitation and manipulation using two opposite airborne ultrasound focusing devices (AUFDs). Each AUFD generates a focal point of ultrasound at an arbitrary position based on the phased array focusing technique. A focal point acts as a ultrasound beam with a finite length, i.e., a focal depth of several centimeters. A localized standing wave is accordingly generated by the opposite AUFDs and traps small particles. This method provides the following features.

- (1) Particles can be manipulated in all directions according to the movement of the localized standing wave based on the phase-delay control.
- (2) The work space is much larger than the previous researches because the ultrasound wave is focused and hence delivered further.
- (3) Particles keep trapped even when the acoustic axis is horizontal because the AUFDs provide a sufficient amplitude of ultrasound.

We also demonstrated that multi acoustic beams can be overlapped by using four AUFDs [2] (**Fig. 1**).

In this study, we extend our previous achievement by generating focal lines instead of focal points. A focal line acts as a ultrasound sheet beam with a finite length. Two sheet beams of localized standing waves are overlapped orthogonally (i.e., four AUFDs are used in all). A standing-wave field with two-dimensionally distributed nodes is generated at the intersection. Being trapped in the nodes, the levitated particles form a single plane in midair (**Fig. 2**). This layer can be used as a floating projection screen and/or physical pixels to achieve real-world-oriented computer graphics [3].

The rest of this paper consists of the detailed description of the AUFD followed by how to generate a focal line and the discussion on a planar formation of levitated particles.

2. Airborne Ultrasound Focusing Device

The AUFD was originally intended to radiate a traveling wave and generate a non-contact force

† star@nitech.ac.jp

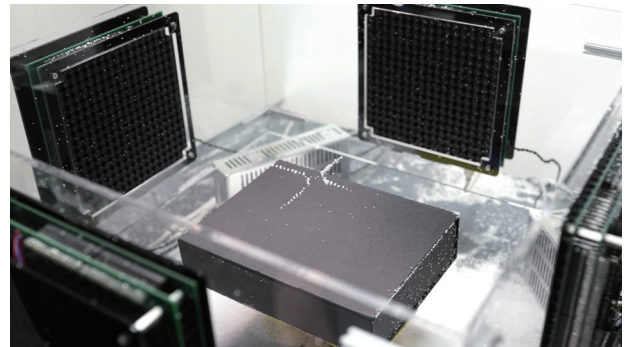


Fig. 1 Previous study: Cross formation [2].

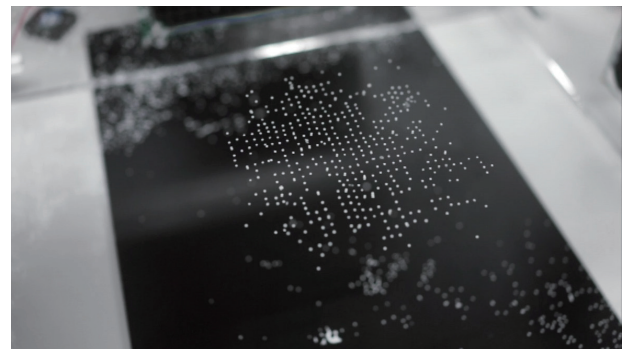


Fig. 2 Current study: Planar formation.

based on the acoustic radiation pressure [4]. In this study, the same devices are used to make a standing wave and trap small particles at the nodes.

The specifications of the latest version of the AUFD are as follows. It is designed to be all-in-one and communicates with a PC via USB. The weight is 0.6 kg. The amplitude of ultrasound is 162 dB SPL at the center of the focal point with 285 transducers (T4010A1, 40 kHz, 10 mm diameter, Nippon Ceramic Co., Ltd.) arranged within a 170×170-mm² square area. Driving signals into the transducers can be updated at the rate of 1 kHz.

A focal line is generated by the slightly modified manner of a focal point. While the adequate phase delays are calculated and set for all of the transducers to generate a focal point, this calculation is conducted only for the transducers in the y-axis on the array and the transducers in the same line along the x-axis are driven at the same phase delays. The narrow width w [m] of the focal line is theoretically derived and written as

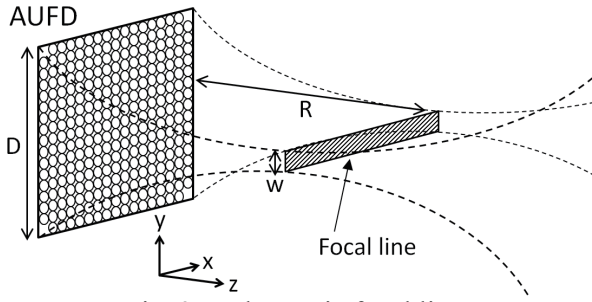


Fig. 3 Ultrasonic focal line.

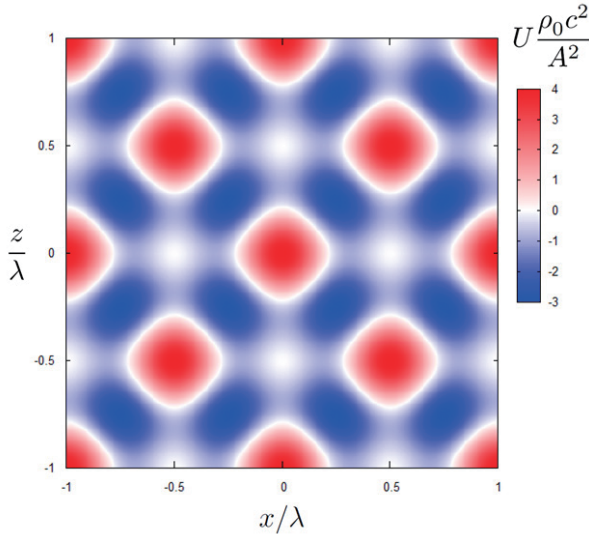


Fig. 4 Grid-like potential energy distribution.

$$w = \frac{2\lambda R}{D} \quad (1)$$

where λ [m] is the wavelength, R [m] is the focal length, and D [m] is the side length of the square array. This equation indicates that the narrow width and the array size are in the relationship of trade-off (**Fig. 3**). On the other hand, the wide width is supposed to be approximately equal to D . As is the case with a focal point, the position of a focal line can be moved three-dimensionally by the adequate control of the phase delays.

3. Planar Formation of Levitated Particles

The planar formation of levitated particles is generated with four AUFUs as follows. First, they are split into two pairs. Two AUFUs in each pair are arranged face-to-face and radiate sheet beams targeting at the same position to generate a wide standing wave which has a single-peaked and wide section. Next, the two wide standing waves are vertically intersected. A grid-like standing wave is generated in the intersection of them. The potential energy distribution of this standing wave is shown in **Fig. 4** where small particles can be suspended at the nodes (minus-value points).

The result with the current prototype system is shown in **Fig. 2**. The distance between the face-to-face AUFUs is 460 mm. A grid-like standing wave is basically generated when the AUFUs generate focal lines at the same position. To be more detailed, it is experimentally found that an offset of focal length of several centimeters increases the stability and the area of the grid-like standing wave. The offset was tentatively set at 50 mm in this paper. The amplitude of ultrasound was set at the maximum. The particles were expanded polystyrene and their diameter was 0.6 mm.

The levitated particles form a grid of at least 30×30 in the current prototype system but there are nodes that are not filled with particles (**Fig. 2**). One of possible reasons is that the suspending force acting in the nodes is insufficient to stabilize the suspended particles against oscillation and/or air flow because the acoustic energy spreads within the focal line. Another possible reason is the distribution of the potential energy. The nodes are not sufficiently separated by the anti-nodes as shown in **Fig. 4** and hence it is easy for suspended particles to move among the neighbor nodes.

A grid-like distribution of particles formed by a two-dimensional acoustic standing wave was also demonstrated in [5]. It was under water and particles manipulated by controlling phases among four transducers. Compared to that, this study brings that phenomenon into air and manipulates particles based on the phased array focusing technique.

4. Conclusion

In this paper, we introduced an extended method of three-dimensional acoustic manipulation. A grid-like standing wave is generated by four ultrasound focusing devices surrounding the workspace. Small particles are trapped at the nodes and also moved three-dimensionally according to the position of the standing wave.

Future work includes (1) optimizing the parameters, (2) evaluating the performance, and (3) exploring applications of the proposed method.

References

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