3P4-8

Implementation of Battery-Powered Compact Mid-Air Acoustic Tweezers System

Yusei Yokoyama[†], and Kan Okubo[*] (Tokyo Metropolitan Univ.)

1. Introduction

There are several methods to levitate a small object without physical contact. Among these methods, acoustic levitation also exists as one of the methods. This approach involves generating a standing wave and/or an acoustic trap through ultrasonic waves, enabling to capture an object in the air.[1)]. Acoustic levitation has high versatility as it can manipulate biological particles ranging from nanometer-sized extracellular vesicles to millimeter-sized multicellular organisms using sound waves[2)].

Many applications of acoustic levitation utilize arrays of ultrasonic transducers, referred to as ultrasonic transducer arrays[1,3-6)]. The primary advantage of ultrasonic transducer arrays lies in the precise control of the resulting acoustic field, achieved by controlling the phase of the output signals for each transducer. By optimizing the phase of the signals delivered to each ultrasonic transducer, even a single-sided array can capture a small object in the air at the millimeter scale[4,6)]. Mid-air acoustic tweezers use a hemispherical ultrasonic transducer array and exploit the geometric properties of the hemisphere in conjunction with adaptive phase and amplitude control of the ultrasonic transducers to achieve fully non-contact levitation of a small object[7,8)].

Mid-air acoustic tweezers function efficiently with a relatively modest number of channels, eliminating the necessity for individual control of numerous ultrasonic transducers. However, achieving levitation of small objects still necessitates a substantially large number of ultrasonic transducers. When assuming the actual non-contact manipulation of these objects, a notable challenge arises due to the sizeable overall system configuration.

In this study, using an FPGA evaluation board and a dedicated circuit to efficiently control the ultrasonic transducer and employing a battery as a power supply, we aim to implement the system with a minimal configuration.

2. Principle

Acoustic levitation is realized through the application of ultrasound to exert an acoustic radiation force on an object. This force is generated by the pressure differences acting on the object's surface upon interaction with sound waves. The stronger the sound wave's amplitude, the greater the acoustic radiation force.

By adaptively adjusting the phase and the amplitude of channels of ultrasonic transducers and leveraging the geometric symmetry of a hemispherical array to focus sound waves at the center, the positional adjustment of a levitated small object becomes achievable, even when utilizing a limited number of channels.

To achieve this, the phase and amplitude of each channel must be precisely optimized to reproduce the reference sound field at the designated position for capturing the small object. A reference sound field is created from the acquisition at the focal point of the array. A weighted least-squares method is used to calculate the optimum phase and amplitude at the acquisition location[7,8)].

In the experimental setup, the initial step involves capturing a small object in proximity to the reflector. Mid-air acoustic tweezers are positioned with their aperture plane parallel to the reflector's surface, allowing them to capture a small object directly below the focal point. Subsequently, a small object gradually moves upwards and ultimately stabilizes at the focal point. The goal is to keep small objects in focus even when they move away from the reflector. This feature allows us to flexibly manipulate small objects across various locations through the precise control of mid-air acoustic tweezers.

3. Experiment

Fig. 1 shows the schematic diagram of the system for half a channel. The mid-air acoustic tweezers system consists of several components, including a controller, an amplifier, a power supply, and the mid-air acoustic tweezers themselves. The controller's function is to oversee the signal phase and amplitude, while the amplifier serves to magnify the signal amplitude and output current. Utilizing FPGA for phase control proves advantageous because of its capacity for logic synthesis and its proficiency in parallel output of multiple signals. For this investigation, the FPGA evaluation board DIGILENT ZYBO Z7-10, equipped with FPGA Xilinx ZYNQ-7010, is used as the controller. Signal amplitude control is performed via the FPGA and the digital potentiometer Analog Devices AD5262(B20kΩ).

Regarding the amplifier, as each channel has

E-mail: [*]kanne@tmu.ac.jp

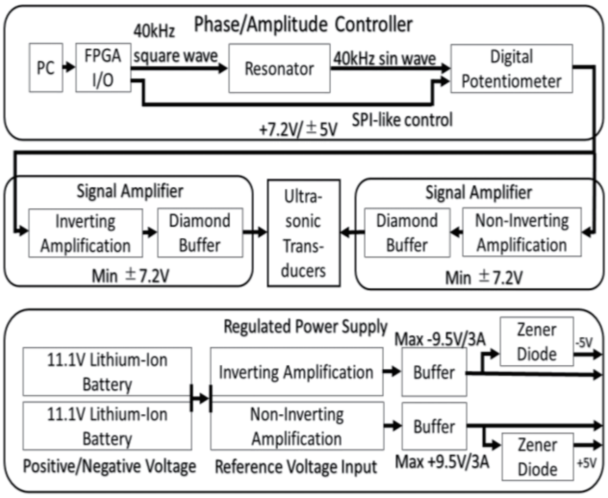

Fig. 1 Schematic diagram of the system for half a channel

multiple ultrasonic transducers as the load, it has been experimentally confirmed that the internal circuit of a conventional audio amplifier becomes unstable and may oscillate. This phenomenon is likely due to different phase output signals intersecting at the ground reference voltage (0V) of the general audio amplifier. Therefore, for stability, the amplifier needs to be constructed with independent circuits for each channel to avoid interference between them. This requires the use of positive and negative power supplies to ensure a stable power source.

The mid-air acoustic tweezers in this research consist of a hemispherical array of 72 ultrasonic transducers (MA40S4S, Murata Manufacturing Co., Ltd.). The smallest number of channels for a potentially successful levitation array is 4 channels, which requires the use of 72 ultrasonic transducers. The hemispherical array is designed using 3D-CAD software such as Fusion360 and fabricated using a 3D printer.

Based on the simulation results, the distance between the mid-air acoustic tweezers and the reflection plate was set to 12mm. Using the phase and amplitude information obtained through numerical calculations, which is optimal for capturing a small object at a specific position, experimental trials were conducted.

4. Result and Discussion

It has been found that even with 72 ultrasonic transducers, mid-air acoustic tweezers system can levitate a polystyrene ball of approximately 2mm in diameter (see Fig. 2). Apprehensions were initially raised about the reduction in acoustic radiation force and a decrease in phase control accuracy due to the fewer number of transducers. This phenomenon might be present in the process of levitating the small object and subsequently capturing them at the focal point. As experimental results, it is suggested that the minimum number of ultrasonic transducers for mid-air acoustic tweezers system is around 72.

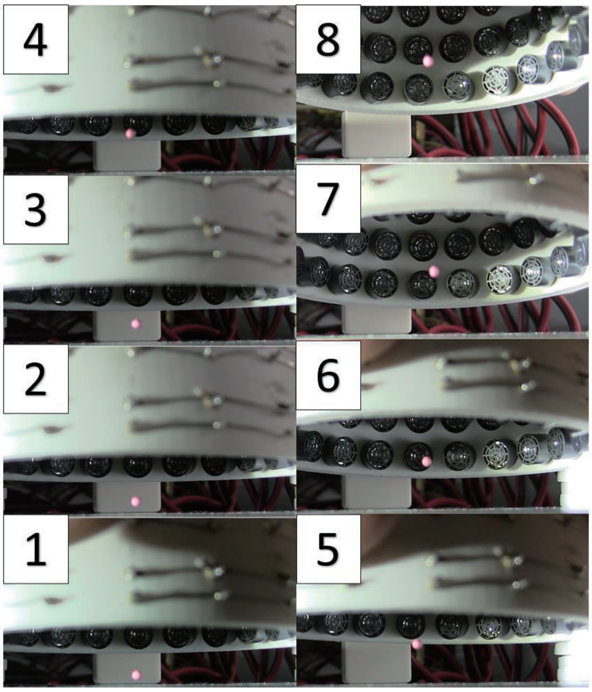

Fig. 2 The process of levitating the polystyrene ball with mid-air acoustic tweezers

5. Conclusion

In this study, we estimated the minimum configuration of the acoustic tweezers and realized the battery-powered implementation.

Acknowledgment

This work was supported by JSPS KAKENHI Grant Number 22K18813.

References

1) A. Marzo, A. Barnes, and B. W. Drinkwater, *Review of Scientific Instruments*, vol. 88, no. 8, pp. 85-105, 2017.
2) A. Ozcelik, J. Rufo, F. Guo, Y. Gu, P. Li, J. Lata, and T. J. Huang, *Nature methods*, vol. 15, no. 12, pp. 1021–1028, 2018.
3) Y. Ochiai, T. Hoshi, and J. Rekimoto, *PloS one*, vol. 9, no. 5, e97590, 2014.
4) A. Marzo, S. A. Seah, B. W. Drinkwater, D. R. Sahoo, B. Long, and S. Subramanian, *Nature communications*, vol. 6, no. 1, pp. 1–7, 2015.
5) A. Watanabe, K. Hasegawa, and Y. Abe, *Scientific reports*, vol. 8, no. 1, pp. 1–8, 2018.
6) A. Marzo and B. W. Drinkwater, *Proceedings of the National Academy of Sciences*, vol. 116, no. 1, pp. 84–89, 2019.
7) S. Kondo and K. Okubo, Jpn. J. Appl. Phys. **60**, SDDD16 (2021).
8) S. Kondo and K. Okubo, Jpn. J. Appl. Phys. **61**, SG8004 (2022).