Design of Ultrasonic Levitation Control System Based on FPGA

Ming Li, Weibo Cai, Xiaoyu Tang*, Tingfeng Li, Linlin Zhu, Yalin Yan

School of Physics and Telecommunication Engineering, South China Normal University, Guangzhou, 510000, China

*Corresponding author’s e-mail: tangxy@scnu.edu.com

Abstract. As a method to achieve containerless processing, the object levitation technique has a broad application prospect in vital research fields. However, the levitation distance of Electromagnetic levitation, near-field acoustic levitation is not far enough to complete containerless processing, and the stability of ultrasonic levitation that use single emitter or single transducer array is still needed to be improved. Therefore, this paper proposes a new embedding electronic system based on FPGA controller to drive a construction of transducer arrays that perpendicularly formed by uniaxial concave sphere and uniaxial biplane. A phase delay algorithm is used on this system to change the position of the stand wave points to move the object smoothly. Furthermore, through experimental validation, this system has a stable signal output to reach the goal of levitation and control.

1. Introduction

The containerless processing technology means producing a force to counteract the gravity of the object by applying a physical field to form a state of no contact with external materials. This technology allows the material to be studied without the influence of the container wall on its physical properties and the influence of different temperatures on its chemical properties, so it is used for the dynamic analysis of liquid drop[1], preparation of new materials [2] and other scenarios.

Acoustic levitation technology is a crucial way to realize containerless operations for follow reasons: Firstly, acoustic levitation technology can levitate more kinds of materials and does not depend on the electromagnetic characteristics of materials. Secondly, acoustic levitation can levitate a substance of the same scale as the wavelength of the acoustic wave. Finally, through the precise control of the control system for the converter, the suspension and manipulation of the object can be realized. So it is an effective way to levitate and control tiny low-density objects through Acoustic waves.

2. Related Work

In 2003, [3] made a hybrid electromagnetic levitation system, which can reach 20 mm to 30 mm’s levitation distance. In 2004, [4] used a piezoelectric vibrator to realize near-field acoustic levitation. The gravity of the load can reach 58 N, and the levitation gap is 18.25 um, which reduces the friction. In 2013, [5] used an ultrasonic emission probe and a plane baffle as the emitter and reflector to form a standing wave sound field, making small particles suspended near the sound pressure node, which is easily affected by the flatness and sound absorption characteristics of the baffle. [6] used the model of a single emitter and concave spherical reflector to realize the suspension of four standing wave nodes.
in the vertical direction. In 2016, [7] proposed to use resonance tube to enhance suspension stability and extended the levitation time by using resonance tube in the experiment.

Previous experimental studies show that near-field acoustic levitation produce large levitation forces, however, the levitation distance is small, so it is not suitable to control small and light objects. Although the single emitter standing wave acoustic levitation can reach higher distance, the levitation stability still needs to be improved. Therefore, our methods use Field Programmable Gate Array (FPGA) to control two concave spherical arrays and two plane arrays.

3. Methods

3.1. Standing wave acoustic levitation

Two ultrasonic waves with the same frequency and velocity and opposite propagation direction can be superposed to form ultrasonic standing wave field. Suppose that the wave equations of ultrasonic wave are as follows:

\[ y_1 = A_0 \cos(\omega t + k_0 z) \]  
\[ y_2 = A_0 \cos(\omega t - k_0 z) \]

The wave equations of the formed standing ultrasonic wave is:

\[ y = y_1 + y_2 = 2A_0 \cos(\omega t) \cos(k_0 z) \]

Where \(y_1, y_2, y\) are vibration displacement of each wave, \(A_0\) is amplitude, \(z\) is distance between particle and launching surface. \(\omega\) is the angular frequency of wave, \(k_0\) is the number of waves.

When the system works, the high-frequency vibration is generated at the transmitting end of the ultrasonic transducer, which forms an acoustic field in the air. The acoustic waves generated by the two opposite arrays are repeatedly superimposed in the sound field space to form a high-strength standing wave sound field, which generates sound pressure. There is a certain sound pressure gradient in the sound field, which makes the suspended object subject to the restoring force pointing to the sound pressure node.

When the distance between launching surface is an integral multiple of half wavelength, the standing wave nodes are produced. The object placed on the node is subjected the acoustic radiation force [8] and realize levitation. Furthermore, it can move through change the initial phase of each acoustic wave.

When the transducer position is fixed, the distance between the transducers is also determined, and then the standing wave sound field can be changed by changing the initial phase of the ultrasonic wave emitted by the transducer to achieve the movement of standing wave node.

For a single transducer, its ultrasonic field is still weak, which is not conducive to the stability of suspended objects. Therefore, multiple transducers are used to form an ultrasonic transducer array to enhance the ultrasonic field strength and improve the stability of levitation and control.

3.2. Transducer Arrays

Two kinds of transducers arrays are used in our methods.

One is the plane array. The ultrasonic transducers on the same plane are arranged to form a plane ultrasonic array. The acoustic waves emitted by the array are superimposed in the space so that the acoustic pressure is enhanced at some points and the levitation ability is improved. In addition, the interference superposition of the acoustic wave in the central axis direction is enhanced, producing an excellent symmetrical focused beam. In our methods, there are 36 transducers in each plane, and the two arrays are aligned to form a more regular sound field.

The other is spherical array. On an open concave spherical surface with a certain curvature radius, ultrasonic transducers are arranged to form a concave spherical ultrasonic array. Compared with the planar ultrasonic transducer array, it has good spherical self-focusing characteristics. Each concave sphere has 36 transducers and the transmitters of every transducer are focused on the center of the sphere.
3.3. FPGA Control

Altera's Cyclone IV FPGA chip EP4CE15F23C8 is used as a control unit. FPGA has been widely used in various fields[9 10]. It uses the logic cell array (LCA), so there are plenty of triggers and I/O pins to be defined and used and its internal multiple circuit modules can be executed in parallel so it can run rapidly.

![System structure diagram](image)

**Figure 1. System structure**

Four 40 kHz differential signals control four ultrasonic arrays and eight IO ports for four pairs of differential signal output. The system clock frequency of 50 MHz is divided to generate multiple required pulse width modulation (PWM) signals.

FPGA control module consists of two circuit logic; one is the signal output logic, which outputs the differential PWM signal to the driver module. The driver module amplifies the signal to drive the four transducer arrays to generate the corresponding phase ultrasonic signal. The other is the control and movement logic, which detects the on board keys and changes the signal phase in the signal output logic according to the detected key.

The 50 MHz clock signal is divided by the signal output logic showed in Figure 2 to generate a 40 kHz signal as the synchronization signal, in which the frequency division ratio is 1250. Counter circulates from 0 to 1249. Step is introduced to divide the counting interval into three subintervals: [0, step], [step, 625 + step], [625 + step, 1249]. high level, low level, and high level are outputted in three subintervals, and four cycles are used to control four arrays separately.

![Output Logic diagram](image)

**Figure 2. Output Logic**
The control and movement logic showed in Figure 3 is used to detect the critical signal. If key1 is pressed, the LED is lighted and the control flag bit is changed, which means that key2 and key3 control the phase of the concave spherical array. On the contrary, key2 and key3 control the left and suitable planar array phase if the LED light is off. When key2 and key3 are pressed, the step values of the two arrays in the horizontal or vertical direction are increased or decreased synchronously to change the waveform generated by the corresponding signal output cycle to achieve the effect of phase shift forward or backward.

![Figure 3. Control Logic](image)

3.4. Signal driving module

The output voltage of FPGA module is 5V, which is not enough to drive the high-power signal generated by the transducer. At the same time, due to the use of arrays, the number of transducers is large, so the driver module is needed to amplify the voltage and power of the signal, so as to improve the signal output strength and the stability of the levitation.

IR2104 and MOSFET are used to build a full bridge driving circuit to amplify the output signal of FPGA chip enough to drive the ultrasonic transducer. When the chip works, the full bridge circuit works. When Q1, Q4 are closed and Q2, Q3 are open, the output voltage is equal to the Q1 access voltage. When switching Q1, Q4 and Q2, Q3 alternately with frequency F, the alternating voltage waveform can be generated to drive the transducer.

![Figure 4. Signal Driving Module Circuit](image)
4. Experiments

In order to verify the correctness of our methods, the program output waveform is firstly simulated on the computer, then the real module is made by using the printed circuit board (PCB) [11]. PCB is a standard circuit manufacture technology in the field of electronic information, which has high reliability. Therefore, PCB is used to control circuits, drive circuits, voltage stabilizing circuits, build instruments, and carry out experiments.

4.1. System Signal Output

The simulation program is written on PC, and the output signal is simulated by Modelsim software. In Figure 5, it can be seen that the waveform phase changes according to the change of the key input signal, which achieves the effect of phase delay in timing.

![Simulation oscillogram](image1)

Figure 5. Simulation oscillogram

The printed circuit board is used to make the circuit. After connecting the output end of the circuit with the transducer array, the output signal of the circuit is tested. In order to verify the feasibility of the drive circuit, the voltage of the power supply is set to 13V and each driving channel is tested by oscilloscope. In Figure 6, it can be seen that the frequency of output signal of FPGA is 40kHz and the peak to peak voltage change to 30.2V from origin 5V, which prove that through the driving circuit, the FPGA output signal voltage is amplified, and the output signal power is improved.

![Driving Module Output Signal](image2)

Figure 6. Driving Module Output Signal

Press the key to offset the output phase and the signal is observed by the oscilloscope. It can be seen from Figure 7 that the signal has a strong load capacity, low noise and complete signal. Therefore, the PWM signal can be completely transmitted to the transducer array.
Figure 7. The Phase Offset

In different input voltages, the signal output voltage of the system is recorded and analyzed. This output voltage curve showed in Figure 8 fits a linear trend line with the correlation coefficient of 0.9984 (maximum is 1), which prove that the output voltage of the system has an excellent linear relationship with the input voltage.

Figure 8. Output Voltage in Different Input Voltage

4.2. Levitation and movement of particles

When the system is working, the phased array drive board emits 40KHz ultrasonic wave. The distance between the two phased array driving plates is fixed to be an integral multiple of the half wavelength of 40KHz ultrasonic wave. The two arrays of the pair synchronously generate 40KHz ultrasonic wave, and several ultrasonic waves with the same frequency and opposite direction are superimposed to form standing wave.

After the standing wave formed, the polyethylene ball is placed in the sound field. This system can stably suspend 1 ~ 4mm polyethylene ball when the power supply voltage is set to 13.0 V.

After the polyethylene ball is levitated stably, it can be moved vertically and horizontal by pressing the key on the device. The displacement of the polyethylene ball is analyzed. It can be seen from Figure 9 that each time the critical delays the phase, the particles can move, and the displacement distance is almost the same, which indicates that the embedded acoustic levitation system has better performance of levitating and moving particles.

Figure 9. Moving Process
The displacement process of the object is analyzed to find stable levitation points in the moving process. It shows in Figure 10 that over 13 stable levitation points are found in the moving process. The average distance that the object move each time is 0.0005 m.

![Figure 10. Levitation points](image)

The experimental results show that the ultrasonic levitation system can improve the suspension stability and verify the feasibility of the movement of small suspended particles.

5. Conclusion
The paper proposes a new ultrasonic array structure based on the FPGA. The phase control algorithm realizes the levitation and movement of particles in the horizontal and vertical directions. The embedded system reduces the complexity and cost of ultrasonic suspension technology equipment and containerless operation. It can operate the material with a radius of several orders of magnitude of ultrasonic length for containerless operation. In the future, it can be applied to the experimental process in related fields and has excellent practical application value.

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