

# Research on Levitation Coupled with Standing Wave Levitation and Electromagnetic Levitation

XiaoYang Jiao<sup>1</sup> – GuoJun Liu<sup>1</sup> – JianFang Liu<sup>1</sup> – Xinbo Li<sup>2,\*</sup> – XiaoLun Liu<sup>1</sup> – Song Lu<sup>1</sup>

<sup>1</sup> Jilin University, College of Mechanical Science and Engineering, China

<sup>2</sup> Jilin University, School of Communication Engineering, China

*In order to solve the problem caused by metal materials' inability to be cooled without contact with other materials after being heated by electromagnetic levitation, a new method is proposed: using a standing wave levitator to levitate the melted metal. The standing wave levitator adopts a concave spherical surface on the emitter and the reflector. Using ANSYS software, the transducer and the standing wave fields were simulated. Based on the simulation, the distribution and the maximum acoustic pressure with different radii of the concave spherical surface on the emitter and the reflector can be obtained, from which the optimal radius was determined. Based on the optimisation, a prototype of a standing wave levitation device was designed and manufactured. Levitation experiments for light and heavy specimens were carried out. It is shown that steel balls can be levitated stably when the distance between the emitter and the reflector is two times that of the wavelength. Next, the standing wave levitator was used in an attempt to levitate a steel ball of 5 mm in diameter after being non-contact heated by electromagnetic levitation. The results show that the method utilising a standing wave levitator to levitate and cool the metal materials after being non-contact heated by the electromagnetic levitation is feasible at this preliminary state.*

**Keywords:** standing wave levitation, ANSYS simulation, electromagnetic levitation, non-contact cooling

## 0 INTRODUCTION

Outer space environments can provide experimental conditions for high vacuum, non-contact and micro-gravity testing, which is appropriate for material solidification to study various kinds of fluid phenomenon [1] and [2]. However, it is far too costly for most researchers to perform space experiments. Consequently, many methods and technologies have been developed to simulate the outer space environment on earth, including acoustic levitation [3], electromagnetic levitation [4], aerodynamic levitation [5], electrostatic levitation [6], optical levitation [7], magnetic levitation [8] and superconducting magnetic levitation [9]. Among these methods and technologies, acoustic levitation has its own distinct advantages, such as good stability, simple construction, no special requirements on the levitated materials, etc. Therefore, research on acoustic levitation is attracting the interest of increasing numbers of researchers.

The principle of acoustic levitation is based on acoustic radiation pressure generated in a highly intense ultrasonic acoustic field, which produces a levitation force to overcome the suspended sample's gravity. In linear acoustics, the sound pressure varies periodically with time and its mean time in a cycle time is zero. However, in highly intense acoustic fields, the nonlinear effect becomes much more significant. In essence, the gravitational force is counteracted by a steady-state acoustic radiation force, as a result of the nonlinear effect in the laminar flow around the levitated specimen when its size is much smaller than

the wavelength of the ultrasound [10]. The levitation force is so large that common solids and liquids of densities thousands of times greater than air can be suspended in air [11]. There is no additional effect on the sample levitated by acoustic levitation force, which in principle can levitate any substance. In areas such as micro-machine technology, biotechnology, and the processing of new kinds of material, the research and application of acoustic levitation has become increasingly important [12]. Acoustic levitation is classified as near-field levitation and standing wave levitation according to the mechanism of ultrasonic levitation.

The levitation height of the specimen suspended by the near-field is in the scale of micrometres, and its levitation force is so large that it can reach tens of kilograms. Furthermore, near-field levitation has been successfully applied to transport objects and rotate rotors without contact [13].

Unlike near-field levitation, a reflector is a part of a standing wave levitation device. The sound waves reflected by the reflector interfere with the forward waves produced by the emitting surface, and standing waves are generated when the distance between the emitting surface and the reflecting surface is an integer multiple of half a wavelength. Compared with near-field levitation, standing wave levitation has more levitation space. However, its levitation force becomes much smaller, and the diameter of the levitated sample can be reduced to millimetre scale.

Electromagnetic levitation technology not only levitates metal samples, but can also heat and melt

\*Corr. Author's Address: Jilin University, School of Communication Engineering, Renmin Road 5988, Changchun, China, xb\_li@jlu.edu.cn

them, preventing other materials contacting with the samples. Therefore, pure metal materials can be obtained. However, the power supply applied to the electromagnetic coils must be turned off when the heating is not needed, and the metal sample needs to cool down. The levitation force on the metal sample also disappears, and the levitated samples are in contact with other materials, which also contaminates them. Several methods have been proposed to solve this problem, such as filling space around the electromagnetic coils with cool inert gases [14], using high drop tubes [15], cold-crucible induction furnaces [16] and so on.

This paper proposes a new kind of method using a standing wave levitator to suspend the metal after heated by the electromagnetic levitation. When the metal sample is levitated and heated by the electromagnetic coils, little or no force from the standing wave levitator is applied on the sample. When the power supply of the electromagnetic coils is turned off, the gravity of the metal is entirely overcome by the standing wave levitation force. The standing wave levitator is usually made by steel, and it also can be easily induced and heated by the electromagnetic coils. Therefore, it is necessary to improve the levitation force and increase the distance between the emitter and the reflector for the standing wave levitator.

In order to improve the levitation force of standing wave levitation, researchers throughout the world have made many significant attempts. Barmatz [17] designed and analysed different resonance chambers of rectangular, spherical and cylindrical geometries. Magill [18] filled the resonance chamber with high pressure gas, and a tungsten carbide sample with a density of 15 g/cm<sup>3</sup> was successfully levitated. Lee [19] arranged multiple transducers in arrays, which levitated a gold particle. Xie and Wei [20] and [21] designed standing wave levitation device with reflector of concave spherical surface, and an Iridium sphere was stably suspended in the standing wave field. Different kinds of liquids were also experimented with as reflectors [22]. A gas stream was used to balance the gravity of the levitating particle whose stability was controlled via a three-axis acoustic levitator [23] and [24]. A piezoelectric transducer with a concave emitting surface and a concave reflector was presented [25] and [26], which increased the levitated object significantly, compared with the traditional single-axis acoustic levitator.

In order to further optimise the acoustic levitator and increase the distance between emitter and

reflector, the emitter and the reflector with different concave radii were analysed via ANSYS, and the pressures of the standing wave field under different parameters are compared in this paper. Based on the optimisation results, the prototype of the levitator with a concave spherical surface on the emitter and reflector was designed and manufactured. In the lab, levitation experiments were carried out using foam and steel balls. Finally, the standing wave levitator was used to suspend the metal materials after being non-contact heated by the electromagnetic coils.

## 1 THEORETICAL ANALYSIS OF STRUCTURAL MODE

### 1.1 Structural Mode

Based on the principle of focused ultrasound, a concave spherical reflecting surface can improve the levitation force of a standing wave levitator and decrease wave diffusion during the delivery process. Therefore, the emitter and reflector of the standing wave levitator are designed as concave spherical surfaces, as is shown in Fig. 1. For the sake of simplification during analysis, an assumption is made that the diameter of the concave spherical reflecting surface is the same as that of the emitting surface.

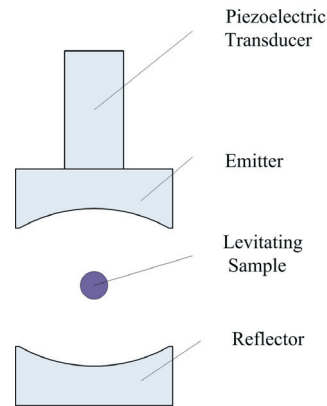


Fig. 1. Structural model

Steel balls can be stably levitated and heated in the electromagnetic coils without contact. The schematic diagram of the coils is shown in Fig. 2. The direction of the electric current in the upper stabilising coils is in opposition to that in the lower levitated coils. The upper coils play the main role of keeping the levitated sample stable and the lower coils provide the levitating force. Generally, electric current with a frequency of tens of thousands hertz flows through the coils, producing alternating electromagnetic fields in the space coated by the coils. Metal samples can

be induced by the alternating electromagnetic field, which generates induced eddies on the surface of the metal sample. In reverse, the induced eddy acts with the electromagnetic field producing the levitation force on the metal sample, and the levitated force can overcome the gravity of the metal sample. At the same time, there is significant heating effect on the metal sample with the induced eddy. Thus, the metal sample can be levitated and heated without contact with other materials.

However, when heating the metal sample is completed and needs to be cooled, the electric current flowing through the coils must be cut off. The heating effect disappears while the levitated force also vanishes, and the metal sample will drop downward. Therefore, the metal sample with a high temperature comes in touch with other materials that may cause contamination. In this paper, a standing wave levitator was used in an attempt to suspend the metal sample after it was levitated and heated by the electromagnetic coils. The schematic diagram is shown in Fig. 3.

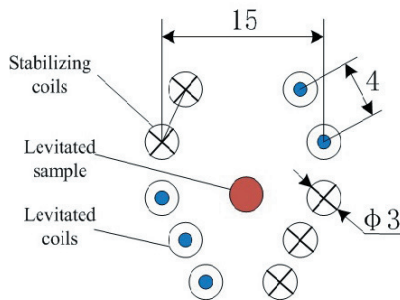


Fig. 2. Schematic diagram of electromagnetic levitation

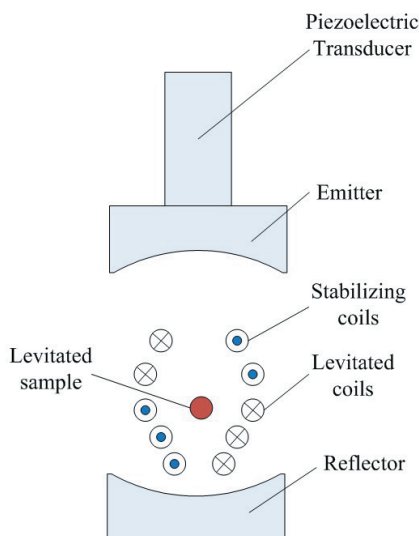


Fig. 3. Schematic diagram of levitation-coupled standing wave levitation and electromagnetic levitation

## 1.2 Vibration Analysis of Concave Spherical Emitting Surface

A sandwich-type structure is generally used in a piezoelectric transducer, which produces a stretching vibration in the axial direction. When the emitting surface is planar, the emitter vibration excites the air, and planar waves are then formed. After reaching the reflecting surface, the planar waves will be reflected. Finally, the planar standing waves come into being when the forward travelling waves are interfered with the reflecting waves. In order to study the vibration model of the concave spherical emitting surface when the piezoelectric transducers produces stretching vibrations in the axial direction, the model analysis of the transducer and emitter were carried out using ANSYS software. The vibration models of the concave spherical emitting surface are shown in Fig. 4. Only half of the transducer and emitter was selected during analysis, due to its symmetrical structure.

The simulation results of Fig. 4 show that the vibration direction of the emitting surface points to the centre position of the spherical surface, and the vibration displacement of the edge is larger than that of the middle. Thus, it can be approximately seen that spherical waves are produced when air is excited by a concave spherical emitting surface. It can be deduced that diffusion to the surrounding space is largely reduced, and the acoustic pressure in the levitating space is enhanced, which will improve the levitation force.

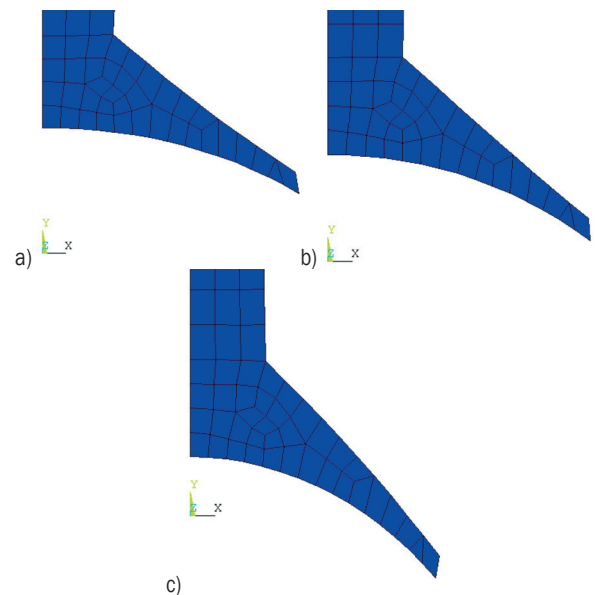


Fig. 4. Vibration model of the concave spherical emitting surface; a) initial model of the emitter, b) emitter model when stretched at the middle, c) emitter model when it was stretched at end

## 2 OPTIMISATION OF THE CONCAVE SPHERICAL SURFACE

As is known, the larger the acoustic pressure, the larger the levitation force. When other parameters are fixed, standing wave pressure differs according to the radii of the concave spherical emitting surface and the reflecting surface. Based on the above conclusion, the piezoelectric transducer, the concave spherical emitting surface and reflecting surface are simulated using ANSYS software, and the pressure value of the standing wave is obtained. By comparing the different acoustic pressure under different radii, the optimal radius of the concave spherical surface can be obtained.

### 2.1 ANSYS Simulation of the Standing Wave Levitator

The designed vibration frequency of the piezoelectric transducer is 20 kHz, of which the emitting surface is considered as a plane. The resonant frequency of the transducer will shift when the emitting surface adopts a concave spherical structure. Thus, it is necessary to obtain the actual vibration frequency through the harmonic analysis method for the piezoelectric transducer and the emitter. Fig. 5 shows dimensions schematic of piezoelectric transducer.

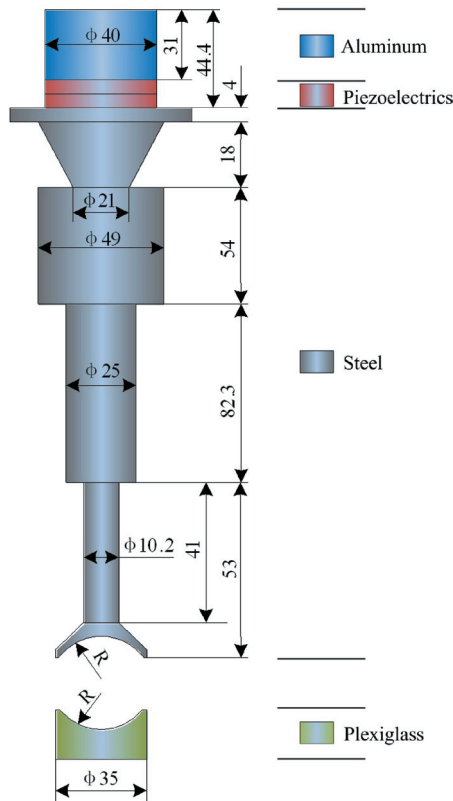


Fig. 5. Dimensions schematic

In the ANSYS model, zero displacement boundary conditions are applied to the nodes at the top of the mechanical amplifier, and the electrical boundary conditions of the 1 V are applied to the piezoelectric materials. The piezoelectric materials are simulated using a PLANE 13 piezoelectric couple-field element, which has displacement and voltage degrees of freedom. An acoustic fluid element, FLUID 29, is used to simulate the air region, which has a pressure degree of freedom. FLUID 29 also can simulate the interaction between the transducer and the air region, which has displacement and pressure degrees of freedom. The air region edge adopts a no-reflection boundary condition and its elements are FLUID 129.

A harmonic analysis is used to simulate the process and phenomenon for the sphere standing wave with the ANSYS software. Firstly, when the radius of the emitting surface is a specific value, the resonant frequency is confirmed after analysing the curve whose amplitude varies with a vibration frequency. Then, the wavelength in the air is calculated, and the distance of the emitting surface and the reflecting surface are adjusted to 1.5 the times of the wavelength. Using ANSYS software again to simulate, the distribution and the maximum pressure of the standing wave in the resonant frequency are obtained. For other emitting surfaces of different radii, the maximum acoustic pressure can be obtained in the same way. Fig. 6 shows the distribution of the standing wave field when the radius  $R$  is 27 mm.

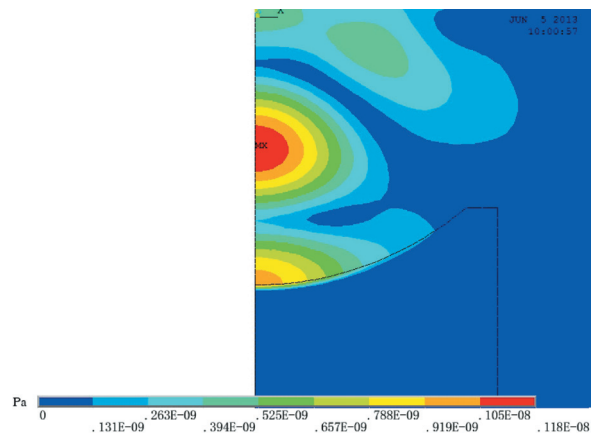


Fig. 6. Standing wave pressure distribution ( $R = 27$  mm, the distance between the emitter and the reflector is 1.5 times of the wavelength)

Fig. 6 shows not only the distribution of the standing wave sound field, but also the maximum acoustic pressure. When  $R$  is set as 27 mm, the maximum pressure is  $1.18 \times 10^{-9}$  Pa (only 1 V voltage



was acted on the piezoelectric chips on the ANSYS simulation). The transducer, the emitting surface and the reflecting surface of different radii (from  $R = 21$  to  $32$  mm) have all been simulated one after another with the space  $R$  of  $1$  mm. Boundary conditions and the input voltage are identical in any radius condition. Fig. 7 shows the curve of the maximum acoustic pressure with different radii of the concave spheres. It can be seen that when  $R$  equals  $27$  mm, the acoustic pressure reaches the maximum, which shows that levitation ability is the strongest under this condition.

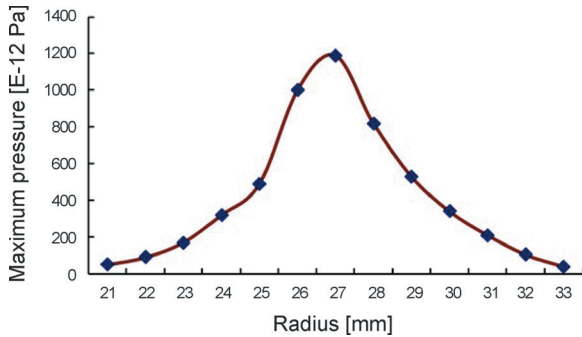


Fig. 7. The max acoustic pressure changes with radius

## 2.2 ANSYS Simulation of the Effect on the Standing Waves Field by the Coils

If the diameter of the electromagnetic coils is too much bigger than that of the levitated specimen, it will lead to unstable levitation. Therefore the electromagnetic coils can only stay inside the standing wave fields space, instead of outside the fields. The electromagnetic coils are between the acoustic levitation emitter and reflector and will disturb the standing wave field. The standing waves will have reflections, interferences, etc. at the coils. ANSYS software continues to be used to simulate the acoustic field affected by the coils.

The simulated model is similar to above, except for the coils between the acoustic levitation emitter and reflector. Zero displacement boundary conditions are applied to the edge of the coils. The air edge contacting the coils is simulated by an acoustic fluid element, FLUID 29, which has displacement and a pressure degree of freedom. Other boundary conditions are similar to above. Fig. 8 shows the simulation results. Compared with the results shown in Fig. 6, the acoustic field obtains some difference when the electromagnetic coils are added between the emitter and the reflector. A strong acoustic field also exists in the space that is surrounded by the electromagnetic coils. Meanwhile, the coils reflect

some acoustic waves, which leads to lower acoustic energy compared to the standing wave field without the coils. Therefore, it can be shown that the maximum acoustic pressure of Fig. 8 is lower than that of Fig. 6. In the levitation experiment coupled with the standing wave levitation and the electromagnetic levitation, a greater voltage should be input to the standing wave transducer.

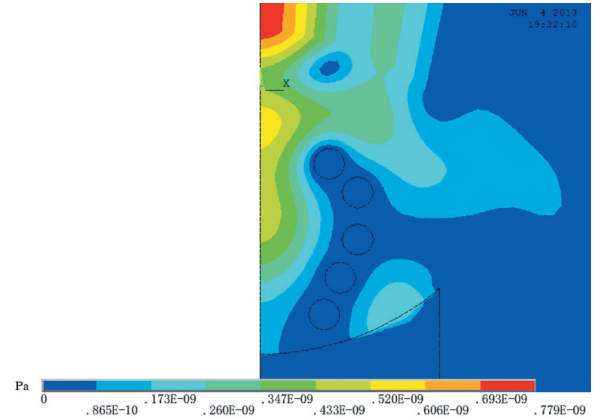


Fig. 8. Distribution of the acoustic field affected by the electromagnetic coils

## 3 STANDING WAVE LEVITATION EXPERIMENT

### 3.1 Standing Wave Levitation Device

According to the optimisation results via the ANSYS software, a standing wave levitator was designed and manufactured (Fig. 9). The piezoelectric transducer is fastened with the adjusting screw at the fixed base, which can be adjusted up and down. The ultrasonic frequency power supply sends an AC signal to the piezoelectric transducer. By turning the adjustment for the reflector, the reflector can be moved up or down, and then the resonant distance between the emitter and the reflector is adjusted.



Fig. 9. Ultrasound standing wave levitation device; 1 ultrasonic-frequency power supply, 2 piezoelectric transducer, 3 adjusting screw, 4 amplitude transformer, 5 emitter, 6 reflector, 7 adjustment for the reflector and 8 fixed base

### 3.2 Sample Levitation Experiment

Light samples similar to foam balls were levitated in the standing wave levitator in order to determine the probable node positions. In Fig. 10, when there are 3, 4 or 6 levitation positions, the light levitated samples are distributed with equal space between them. The samples nearby the emitter are off the axial line and others are on the axial line. Several items can be levitated in any position of the annular nodes. As a result of the annular potential dispersing power of the standing waves, it can only levitate some light materials. A high density specimen, such as a steel sphere, cannot be levitated in the annular potential, as shown in Fig. 11, which can only levitate steel spheres at other positions.

When the distance is near 34.9 mm, i.e. about twice the wavelength, two steel balls (diameter 5 mm) can be levitated at the two positions near the reflector or the middle locations, as shown in Figs. 11a and b. However, the same steel sphere cannot be levitated at the rest position at the same time. The levitation state of the two steel balls is steady. However, owing to the smaller restoring force, the levitation can be easily destroyed by exterior disturbances. Moreover, as the distance becomes longer, the restoring force and stability of the levitated sample will become worse.

In Fig. 11c, three steel balls of 3mm diameter can be suspended at three positions near the reflector at the same time when the distance between the emitter and the reflector is twice the wavelength. The levitator presented by Andrade et al. [25] and Baer et al. [26] can levitate three steel spheres of 2.5 mm diameter when the distance between the emitter and the reflector is 1.5 times that of the wavelength. The levitating number of the same sample is a powerful reference that can be used as an evaluation method for the working stability and levitation ability of a standing wave levitation device. The levitation force and stability of the standing wave device presented in this paper are observably improved.

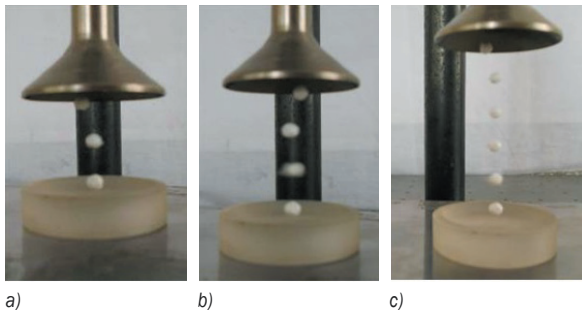


Fig. 10. Light specimen levitated by standing wave

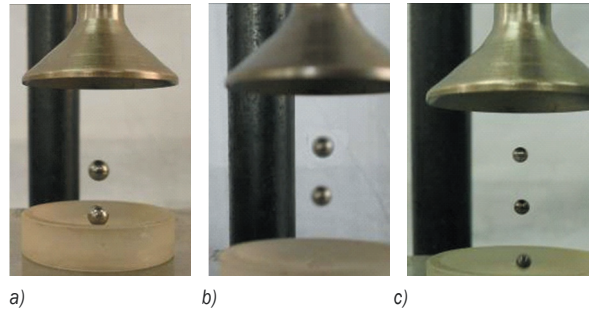


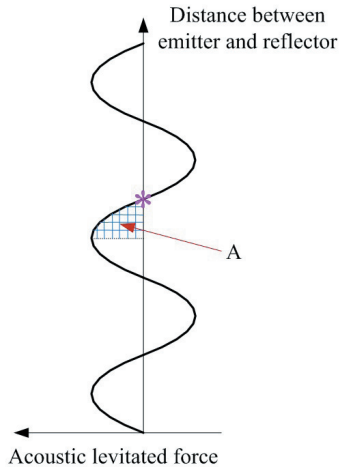
Fig. 11. Steel spheres levitated by standing wave

When the distance continues to increase, no steel sphere can be levitated at any position of the standing wave field. The reason is that too many waves spread outside of the levitation space when the distance increases, which weakens the power of standing wave. If a resonance tube is used in the test, the results will be better. However, it is difficult to place specimen in the standing wave field.

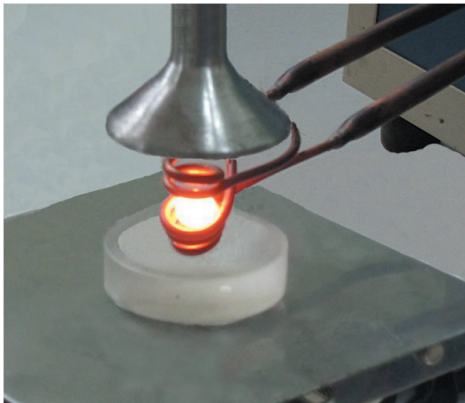
### 3.3 Electromagnetic Levitation Experiment Coupled with Standing Wave Levitation

In the coupled levitation, the distance between the emitter and the reflector of the standing wave levitator is adjusted to two times that of the wavelength and a steel ball of 5 mm diameter can be stably levitated at the second levitation position near the reflector. The axial line of the electromagnetic coils should coincide with that of the standing wave levitator. The levitated position of the steel ball in the electromagnetic coils should be coincident with the second levitated position near the reflector in the standing wave levitator, as shown ‘\*’ in Fig. 12. The relationship between the levitated force and the distance between the emitter and the reflector is in accordance with the sine equation [27]. As shown in Fig. 12, when the steel ball is levitated and heated by the electromagnetic coils, the steel ball is seated at the second node of the standing wave levitator and the force on it from the standing waves is zero or extremely little. When the heating of the steel ball is completed, the electric current input to the electromagnetic coils is decreased. The electromagnetic force on the steel ball will lessen, and the ball will start to move downward gradually. At the same time, the acoustic force on the steel ball from the standing wave levitator will become larger until the electric current of the electromagnetic coils is entirely cut off and the steel ball is levitated by the standing wave levitator alone. In this way, the steel ball is cooled to room temperature without contact with any other materials. In the process of

transferring the levitated force on the steel ball from the electromagnetic force to acoustic force, the drop distance of the sample is about  $1/8$  of the wavelength (2.2 mm) and the motion is smooth and steady. The photo of the levitation coupled the standing wave levitation and the electromagnetic levitation is shown in Fig. 13.



**Fig. 12.** Schematic diagram of the sample position transformation in coupled levitation; '\*' is the position where the acoustic levitated force is zero. 'A' is possible positions where the metal ball is levitated by the acoustic levitated force alone



**Fig. 13.** Photo of the levitation coupled the standing wave levitation and the electromagnetic levitation

When the steel ball, at a higher temperature, is levitated and cooled in the standing wave levitator, it is extremely important to adjust the resonant acoustic field. Since the change of the temperature leads to the shift of the wavelength, the distance between the emitter and the reflector needs to be adjusted to accommodate the resonance condition. However, it is difficult to adjust the distance in time by hand. In fact, the distance between the emitter and the reflector can be set a little smaller. When the temperature decreases,

the resonance condition will be weakened, and the levitation force on the levitated sample will become correspondingly smaller. Therefore, the levitated position will also move downward. Thus, when the downward motion of the steel ball is observed, it immediately shows a decrease in the distance between the emitter and the reflector. Simultaneously, enough sound pressure must be kept. In this way, the standing wave field can be balanced at an approximation resonance condition [28]. In this method, the steel ball at a higher temperature was cooled to room temperature without contact with any other materials. It is shown that the standing waves can be used to suspend the metal sample that has been levitated and heated by the electromagnetic coils.

#### 4 CONCLUSIONS

With the purpose of further optimisation of the acoustic levitator and the levitation via coupling standing wave levitation and electromagnetic levitation, the emitter and the reflector with different concave radii were analysed with ANSYS software. The formation of the standing waves was simulated. The distribution and the maximum acoustic pressure were ascertained with different radii of the concave spherical surface on the emitter and the reflector. The acoustic pressure of different levitators was compared, and the optimal radius  $R = 27$  mm for this levitator was determined.

Based on the optimisation, a standing wave levitator was manufactured. With this device, levitation experiments for light and heavy specimens were carried out. Many types of light foams could be simultaneously levitated at discrete node positions; the foam levitated near the emitter deviated from the axial line. However, steel balls could not be levitated at the node position near the emitter. When the distance between the emitter and the reflector equalled twice that of the wavelength about 34.9 mm, three steel balls of 3mm diameter could be simultaneously levitated in three disparate node positions, excluding the position near the emitter. Compared with other standing wave levitation devices, the levitation capability of the levitator presented in this paper was considerably enhanced.

Following that, an attempt was made to use the standing wave levitator to levitate a steel ball of 5 mm diameter after non-contact heating via electromagnetic levitation. Though the heated steel ball was not particularly stable when it was cooled, the coupled levitation experiment could be successful if the distance between the emitter and the reflector was



suitably adjusted. The results show that it is feasible preliminarily by using standing wave levitator to levitate and cool the metal materials after non-contact heating via the electromagnetic levitation.

## 5 ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China (Grant No. 51075181).

## 6 REFERENCE

- [1] Gao, J.R., Cao, C.D., Wei, B. (1999). Containerless processing of material by acoustic levitation. *Advances in Space Research*, vol. 24, no. 10, p. 1293-1297, DOI:10.1016/S0273-1177(99)00736-X.
- [2] Urevc, J., Koc, P., Stok, B. (2011). Characterization of material parameters used in the mathematical modelling of arc welding and heat treatment processes *Transactions of Famena*, vol. 35, no. 4, p. 1-14.
- [3] Brandt, E.H. (2001). Suspended by sound. *Nature*, vol. 413, no. 6855, p. 474-475, DOI:10.1038/35097192.
- [4] Tsukada, T., Sugioka, K., Tomoya, T., Fukuyama, H., Kobatake, H. (2009). Effect of static magnetic field on a thermal conductivity measurement of a molten droplet using an electromagnetic levitation technique. *International Journal of Heat and Mass Transfer*, vol. 52, no. 21-22, p. 5152-5157, DOI:10.1016/j.ijheatmasstransfer.2009.04.020.
- [5] Hennet, L., Cristiglio, V., Kozaily, J., Pozdnyakova, I., Fischer, H E., Bytchkov, A., Drewitt, J.W.E., Leydier, M., Thiaudiere, D., Gruner, S., Brassamin, S., Zanghi, D., Cuello, G.J., Koza, M., Magazu, S., Greaves, G.N., Price, D.L. (2011). Aerodynamic levitation and laser heating: Application at synchrotron and neutron sources. *The European Physical Journal - Special Topics*, vol. 196, no. 1, p. 151-165, DOI:10.1140/epjst/e2011-01425-0.
- [6] Kordel, T., Holland-Moritz, D., Yang, F., Peters, J., Unruh, T., Hansen, T., Meyer, A. (2011). Neutron scattering experiments on liquid droplets using electrostatic levitation. *Physical Review B*, vol. 83, no. 10, p. 104205:1-9, DOI:10.1103/PhysRevB.83.104205.
- [7] Kohira, M., Isomura, A., Magome, N., Mukai, S., Yoshikawa, K. (2005). Optical levitation of a droplet under a linear increase in gravitational acceleration. *Chemical Physics Letters*, vol. 414, no. 4-6, p. 389-392, DOI:10.1016/j.cplett.2005.08.083.
- [8] Geim, A.K., Simon, M.D., Boamfa, M.I., Hefinger, L.O. (1999). Magnetic levitation at your fingertips. *Nature*, vol. 400, no. 6742, p. 323-324, DOI:10.1038/22444.
- [9] Liu, J.H., Wang, Q.L., Yan, L.G. (2009). Analysis of force characteristics of a superconducting ball in a given magnetic field. *Physica C: Superconductivity*, vol. 469, no. 13, p. 756-759, DOI:10.1016/j.physc.2009.04.006.
- [10] Brandt, E.H. (1989). Levitation in Physics. *Science*, vol. 243, no. 4889, p. 349-355, DOI:10.1126/science.243.4889.349.
- [11] Xie, W.J., Cao, C.D., Lu, Y.J., Wei, B. (2002). Levitation of Iridium and Liquid Mercury by Ultrasound. *Physical Review Letters*, vol. 89, no. 10, p. 104304:1-4, DOI:10.1103/PhysRevLett.89.104304.
- [12] Kozuka, T., Yasui, K., Tuziuti, T., Towata, A., Lida, Y. (2007). Noncontact Acoustic Manipulation in Air. *Japanese Journal of Applied Physics*, vol. 46, no. 7B, p. 4948-4950, DOI:10.1143/JJAP.46.4948.
- [13] Ryuto, Y., Manabu, A., Hideki, T., Takehiro, T. (2011). Novel transfer method using near-field acoustic levitation and its application. *Japanese Journal of Applied Physics*, vol. 50, no. 7, p. 07HE29:1-5, DOI:10.1143/JJAP.50.07HE29.
- [14] Malekzadeh, M., Halali, M. (2011). Production of silver nanoparticles by electromagnetic levitation gas condensation. *Chemical Engineering Journal*, vol. 168, no. 1, p. 441-445, DOI:10.1016/j.cej.2010.12.081.
- [15] Cadirli, E., Herlach, D.M., Volkmanb, T. (2010). Characterization of rapidly solidified Ni-Si and Co-Al eutectic alloys in drop tube. *Journal of Non-Crystalline Solids*, vol. 356, no. 9-10, p. 461-466, DOI:10.1016/j.jnoncrysol.2009.12.019.
- [16] Takeuchi, M., Arai, Y., Kase, T., Nakajima, Y. (2013). Corrosion study of a highly durable electrolyzer based on cold crucible technique for pyrochemical reprocessing of spent nuclear oxide fuel. *Journal of Nuclear Materials*, vol. 432, no. 1-3, p. 35-41, DOI:10.1016/j.jnucmat.2012.07.048.
- [17] Barmatz, M., Collas, P. (1985). Acoustic radiation potential on a sphere in plane, cylindrical, and spherical standing wave fields. *The Journal of the Acoustic Society of America*, vol. 77, no. 3, p. 928-945, DOI:10.1121/1.392061.
- [18] Magill, J., Capone, F., Beukers, R., Werner, P., Ohse, W. (1987). Pulsed laser heating of acoustically levitated microspheres under pressure. *High Temperatures- High Pressures*, vol. 19, no. 5, p. 461-471.
- [19] Lee, M.C., Feng, I. (1982). Acoustic levitating apparatus for submillimeter samples. *Review of Scientific Instrument*, vol. 53, no. 6, p. 854-859, DOI:10.1016/1.1137068.
- [20] Xie, W.J., Wei, B. (2002). Dependence of acoustic levitation capabilities on geometric parameters. *Physical Review E*, vol. 66, no. 2, p. 026605:1-11, DOI:10.1103/PhysRevE.66.026605.
- [21] Xie, W.J., Cao, C.D., Lu, Y.J., Wei, B. (2002). Levitation of Iridium and Liquid Mercury by Ultrasound. *Physical Review E*, vol. 89, no. 10, p. 104304:1-4.
- [22] Hong, Z.Y., Xie, W.J., Wei, B. (2011). Acoustic levitation with self-adaptive flexible reflectors. *Review of Scientific Instrument*, vol. 82, no. 7, p. 074904:1-5, DOI:10.1063/1.3610652.
- [23] Weber, J.K.R., Hampton, D.S., Merkley, D.R., Rey, C.A., Zatarski, M.M., Nordine, P.C. (1994). Aero-acoustic levitation: A method for containerless liquid-



- phase processing at high temperatures. *Review of Scientific Instrument*, vol. 65, no. 2, p. 456-465, DOI:10.1063/1.1145157.
- [24] Stephens, T.L., Budwig, R.S. (2007). Three-axis acoustic device for levitation of droplets in an open gas stream and its application to examine sulfur dioxide absorption by water droplets. *Review of Scientific Instrument*, vol. 78, no. 1, p. 014901:1-8, DOI:10.1063/1.2424454.
- [25] Andrade, M.A.B., Buiocchi, F., Adamowski, J.C. (2010). Finite element analysis and optimization of a single-axis acoustic levitator. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 57, no. 2, p. 469-479, DOI:10.1109/TUFFC.2010.1427.
- [26] Baer, S., Andrade, M.A.B., Esen, C., Adamowski, J.C., Schweiger, G., Ostendorf, A. (2011). Analysis of the particle stability in a new designed ultrasonic levitation device. *Review of Scientific Instruments*, vol. 82, no. 10, p. 105111:1-7, DOI:10.1063/1.3652976.
- [27] King, L.V. (1934). On the acoustic radiation pressure on spheres. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, vol. 147, no. 861, p. 212-240, DOI:10.1098/rspa.1934.0215.
- [28] Xie, W.J., Wei, B. (2001). Space environment simulation for material processing by acoustic levitation. *Chinese Physics Letters*, vol. 18, no. 1, p. 68-70, DOI:10.1088/0256-307X/18/1/324.