Preliminary experimental studies on particles levitation in air under the effect of wideband ultrasound waves

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Abstract. We investigated the possibility of controlled levitation of particles in the air under the influence of wideband ultrasonic waves. We examined the interference field formed by the radiation of counterpropagating emitters of signals with linear frequency modulation. It is proposed to use two counter-directed emitter arrays focused at the center. The focusing of the emitter arrays is achieved due to the fact that the elements of the arrays are placed on the surface of the sphere in a certain sector. Then the focus point is the center of the sphere at any radiation frequency. When a common-mode wideband signal is applied to all elements of the array, focusing of the wideband signal is achieved in the center of the sphere. When a monochromatic signal is applied, a levitation region elongated along the axis of the system is formed. We consider the case when the distance between the radiating gratings is several times larger than the size of the aperture of the gratings. For wideband signals particles are grouped into a single stable pressure node of standing waves in the center of the system. This provides a single local minimum potential for the selective control of an individual particle. Moreover, a force arises that draws particles into the central region.

1. Introduction

Currently, work is underway on ultrasonic particle levitation [1-3]. Already developed ultrasonic acoustic tweezers [4]. Developed installations for the
levitation of particles whose sizes are commensurate with the wavelength and objects whose sizes are several times larger than the wavelength. There are methods of acoustic levitation of various variations, for example, in a standing wave between a single source and a reflector [5]. Levitation in this work is carried out due to the spherical shape of the reflector, which, at a certain distance, forms standing waves in which levitation occurs. This approach does not require focusing of the field; however, it is not possible to control particles by changing the emitted signal. In [6], levitation occurs in a standing wave between an ultrasonic field source and a special object printed on a 3D printer. The special geometry of the scatterer allows you to form a given field distribution and keep the particles in a stable position. However, this approach has certain difficulties, such as the need for a certain geometry of material for each field distribution. In [7–9], solutions for narrow-band levitation of particles using lattices located along the faces of a cube (two or four lattices) are presented. With such configurations, three-dimensional levitation is achieved due to standing waves between the arrays. Such approaches make it possible to control particles along the axis of focusing, and also in some cases up and down. However, the formed levitation regions in such cases are located in the nodes at the same distance from each other, which requires additional structural changes to form the necessary particle distribution. We also previously conducted experiments on narrow-band levitation [10] of small particles and linear segments longer than the wavelength. However, narrow-band levitation has a feature associated with the periodic pattern of levitation regions in standing waves [11].

In this paper, we propose a method of levitation of particles by broadband ultrasonic waves. This approach allows particles to be pulled into one area without creating many periodic areas of levitation. Thus, it is planned to create one focus spot and, due to this, transfer particles to a single localized region.

2. Mathematical description

Let us consider an acoustic levitation system based on two counter emitter focused at one point arrays. Due to the placement of emitters on a sector of the surface of the sphere, the field is focused at all frequencies to the center of the sphere of 18 cm radius (fig. 1). It is proposed to use a wideband signal in the form of a signal with linear frequency modulation (LFM or chirp signal) to ensure the only stable position of the levitating particle between two focused emitter arrays.
We consider chirp signal with increasing frequency. As an experimental setup, two counter-directed gratings located at a distance of 36 cm will be considered. It is planned that such a configuration will create a field attracting particles to the center.

Consider a signal with linear frequency modulation of the form:

\[
P(t) = P_0 \cos \left( \omega_0 t + \frac{\Delta \omega t^2}{2T} \right) = \text{Real} \left[ P_0 \exp \left( i \omega_0 t + i \frac{\Delta \omega t^2}{2T} \right) \right],
\]

where \( P_0 \) – magnitude of acoustic pressure; \( \Delta \omega \) – frequency range of wideband signal; \( \omega_0 \) – minimal cyclic frequency of emitting signal; \( T \) – temporal signal length. It is assumed, that the signal is repetitive with time period \( T \).

It is proposed to apply antiphase signals to opposite emitting arrays in order to provide a stable node of standing pressure waves in the center.

With the interference of oncoming wideband plane waves, an interference field is formed:

\[
U(t,x) = P \left( t - \frac{R-x}{c} \right) - P \left( t - \frac{R+x}{c} \right),
\]

where \( R \) – radius of sphere at which the emitters are placed. The beginning of x axis is measured from the center of the system (from the focus point).

If we apply (1) for (2) we gain:
If the same LFM signal is supplied to both counter-directed arrays, then exactly in the middle between the arrays the destructive interference of counterpropagating waves at the same frequency is always ensured. What forms node of standing wave in the center and antinodes nearby. It can be seen from (3) that, when \( x = 0 \) a stable node of a standing wave arises, which remains at all time instants. When shifted from the center, the interference of counterpropagating waves at different frequencies occurs. Moreover, if you shift along the axis of the system to the left array, interference of a higher-frequency signal from the left array with a signal at a lower frequency from the right array will be observed. With this interference, a quasi-standing wave is formed with nodes gradually moving to the right. Moreover, the speed of the nodes will increase with a strong deviation from the center. Similarly, when shifted to the right, the movement of interference pressure nodes to the left will be observed. Such a distribution of the field forms the field of forces of the pulling particle in the center between the arrays. This will ensure the only stable position of the particles in the center. If it is necessary to move particles along the axis of symmetry between the arrays, it is proposed to trigger signals in oncoming arrays with a time shift. Then the point of stable destructive interference of the field will shift towards the array, where the signal is triggered with a delay. It is assumed that the signals are reproduced cyclically, since it is impossible to emit LFM with an infinitely increasing frequency. The longer the repetition period, the more stable the particle levitation. When switching the radiation frequency from maximum to minimum, a jump in the position of local nodes will be observed. In this case, a violation of levitation may occur, however, since the restructuring occurs quickly, the particles do not have time to fall out of the levitation area. Since a relatively narrow frequency band from 38 kHz to 43 kHz is considered in a real levitation setup, jumps in the position of the nodes will be insignificant.

3. Experiment

We have carried out experimental studies, that confirmed the applicability of the proposed concept. Figure 2 shows a photograph of the levitation of
polystyrene particles in an ultrasonic field with LFM modulation from 38 to 43 kHz. Particles are located in a thin disk in the center of the system. The distance between the emitter arrays is 36 cm, in each grating there are 91 emitters MA40S4S arranged in a hexagonal grid. As expected, a grouping of particles into one node of standing waves from oncoming emitters is observed. When backfilling particles from the side, they were drawn into the central region, where their position was stabilized.

Fig. 2. Picture of levitating particles in a wideband ultrasonic field

Fig. 3 shows a picture of the supply of particles to the levitation region. It can be seen that the particles are captured by the ultrasonic field, even when they get away from the center. In this case, they get horizontal acceleration and collide with stabilized particles, which leads to temporary chaotic oscillations of particles around the central node of standing waves.
Falling particles

Captured

passing
particles

stabilized
particles

Fig. 3. Photo of the process of feeding particles into the levitation region where you can see the process of fall, trap and stabilization of particles

A small number of particles stabilizes in the nodes of the standing waves near the central node. Some particles fly through the field focus area due to the high rate of incidence.

After stabilization of the particles during the experiment, the time delay was adjusted between the signals of the opposing emitter gratings. Changing the delay led to the displacement of levitating particles along the axis of focusing.

Future Directions

In the future, it is proposed to conduct experiments on wideband levitation of particles in three-dimensional space. This technology is planned to be applied to the technology of acoustic tweezers and three-dimensional printing.

Conclusion

A method for providing acoustic levitation in a wideband ultrasonic field is proposed. It has been theoretically and experimentally shown that it is advisable to use signals with linear frequency modulation, which provide a stable levitation area when using two counter-focus antiphase focused emitters. During the experiments, stable levitation of the styrofoam particles was observed in the center of the emitter system, where a constant node of standing waves is formed. When particles fall away from the center, a force arises that draws particles into the center. Control over the movement of particles along the axis is possible due
to a change in the relative delay in reproducing the signals of the opposite arrays.

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