VIBRATING-CHAMBER LEVITATION SYSTEMS

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ABSTRACT

Systems are described for the acoustic levitation of objects, which enable the use of a sealed rigid chamber to avoid contamination of the levitated object. The apparatus includes a housing forming a substantially closed chamber, and means for vibrating the entire housing at a frequency that produces an acoustic standing wave pattern within the chamber.

14 Claims, 5 Drawing Figures
VIBRATING-CHAMBER LEVITATION SYSTEMS

ORIGIN OF INVENTION

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of provisions of Public Law 96-517 (35 USC 202) in which the contractor has elected not to retain title.

BACKGROUND OF THE INVENTION

Acoustic levitation is useful to support an object without touching it with a solid support that could contaminate it, especially when the object is heated to a temperature at which it is molten. Two techniques have been used to couple an acoustic transducer to the atmosphere within a chamber. One technique is to place a transducer in direct contact with the atmosphere within the chamber, and the other is to place the transducer in contact with a chamber wall to vibrate the wall. When the acoustic transducer is in direct contact with the atmosphere in the chamber, there can be danger of contamination of the atmosphere by the transducer. In addition, a temperature gradient must be established along the chamber if the object is heated to a high temperature, since available transducers cannot withstand high temperatures. Where the transducer directly vibrates a wall of the chamber, there can be a loss of efficiency by the need to transmit acoustic energy through a chamber wall. A system for establishing an acoustic standing wave pattern within a chamber, without the need to place a transducer in contact with the atmosphere of the chamber or to pass the vibrations through a flexible wall of a chamber, could aid in avoiding contamination of the levitated object and enable more intense standing wave patterns to be generated.

SUMMARY OF THE INVENTION

In accordance with one embodiment of the present invention, a method and apparatus are provided for establishing an acoustic standing wave pattern within a housing that forms a chamber, in a manner that minimizes contamination of the chamber and which enhances the generation of acoustic waves of high intensity within the chamber. The apparatus includes a means for rapidly moving substantially all of the housing back and forth along at least one axis, at a frequency that produces an acoustic standing wave pattern within the chamber.

The novel features of the invention are set forth with particularity in the appended claims. The invention will be best understood from the following description when read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a sectional view of an acoustic levitation system constructed in accordance with the present invention.

FIG. 2 is a perspective view of a levitation system of another embodiment of the invention.

FIG. 3 is a sectional view of an acoustic levitation system which includes a spherical chamber, in accordance with another embodiment of the invention.

FIG. 4 is a sectional view of an acoustic levitation system with a chamber having angled upper walls, in accordance with another embodiment of the invention.

FIG. 5 is a sectional view of an acoustic levitation system which includes a chamber which is largely cylindrical but with a curved axis, in accordance with another embodiment of the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 illustrates an acoustic levitation system which includes a housing that forms a levitation chamber which surrounds an object. The object is held near the position against the force of gravity, by the forces applied by an acoustic standing wave pattern generated by a transducer. The transducer may be any of a variety of types, such as a piezo-electric type in which a crystal undergoes changes in thickness, or a loudspeaker coil type. The transducer has an upper surface that vibrates up and down, and the housing is fastened to that surface. As a result, the entire housing, including the bottom and top walls, moves back and forth along a vertical axis in synchronism. If a proper frequency is chosen, an acoustic standing wave pattern will be produced within the chamber, which has a minimum acoustic force potential at the location.

The lowest acoustic frequency which is resonant to the height of the chamber, is one which produces a wave length indicated at 30, which is equal to twice the height of the chamber. In this lowest mode, which may be referred to as the first mode, the pressure at the bottom wall 24 must be a maximum at the same time as the pressure at the upper wall 26 is a minimum. This occurs when vibrating the entire chamber, since the bottom wall 24 is moving upward to compress the gas at the bottom of the chamber at the same time as the upper wall 26 is moving upward to minimize the pressure at the top of the chamber (its pressures are out-of-phase). If only the bottom wall of the chamber were vibrated, as in prior art levitation systems, then the next higher or second mode, wherein the wavelength indicated at 34 equals the height of the chamber, would also be resonant to the height of the chamber. However, the second mode is not resonant to the chamber when the top and bottom walls are vibrated in synchronism (both move up at the same time, and both move down at the same time), because the wavelength 34 requires maximum acoustic pressure at the bottom and top of the chamber at the same time (i.e. the pressures are in phase). The third lowest, or third mode, which has a wavelength indicated at 36 equal to two thirds the height of the chamber, is also resonant to the system. The third lowest mode is similar to the fundamental in that the pressure at the top of the chamber is minimum at the time that the pressure at the bottom is maximum. Thus, the lowest mode indicated at 30, and the other higher odd modes are resonant to the height of the chamber when the entire chamber is vibrated vertically.

The acoustic levitation of the object by vibrating the entire chamber to move the lower and upper walls together, has an advantage over prior systems of enabling a sealed chamber to be used while also efficiently coupling vibrations of the transducer to the gas within the chamber. In one type of prior system, acoustic energy was transmitted from a transducer through a tube that passed through one wall such as 24 of the chamber. The transducer therefore was in direct contact with gas in the chamber, and outgassing of certain diaphragm transducers could result in contamination of the gas within the chamber. In another type of prior art system, a transducer was coupled to the middle of a thin flexible
wall to vibrate it. This required the use of a wall which could vibrate, and there was often poor transmission of acoustic energy through such a wall. By vibrating the entire chamber, applicant enables the use of a rigid chamber without any openings in it, to enclose and levitate an object. It is also noted that since applicant vibrates both opposite walls 24 and 26 of the chamber, there is a greater intensity of sound within the chamber than when only one wall of the chamber is vibrated.

The system of FIG. 1 shows levitation in only the vertical direction, but not in sideward directions. While such sideward levitation can be accomplished by other means, it is convenient to use a single transducer to levitate in all three dimensions. This can be accomplished by using resonant chambers that have some section of their walls that is not parallel or perpendicular to the axis of vibration. Under these conditions, the surface motion of this wall section can be separated into components that may lead to chamber resonances that are not only along the axis of vibration.

FIG. 2 shows a housing 40 with a chamber 42 of parallelepiped shape of rectangular cross-sections, which is vibrated by a transducer 44. The chamber is oriented so that the x and y axes are angled by 45° each from the vertical and the z axis is angled 70° from the vertical. When the chamber is vibrated vertically along an axis 46, an acoustic standing wave pattern will be established to fix the position of an object within the chamber. The resonant frequency is one which produces a wavelength equal to

$$\lambda = \frac{2\pi R}{l_1^0 + l_2^0 + l_3^0 - 4l_4^0 - 2},$$

where \(l_1, l_2, \) and \(l_3\) are the dimensions of the chamber along the x, y, and z axis, for the above angles.

For a parallelepiped having sides of lengths \(l_1, l_2,\) and \(l_3\), equations can be given to the optimum levitation along most of the chamber height. This type of chamber with upper walls at \(12,\) equations can be given to the optimum levitation along most of the chamber height. This type of chamber has upper walls at 76 that are angled towards one another in an upward direction, to produce a minimum acoustic potential surface 78 which is curved. An object 80 will be levitated on or near the surface, and will be urged toward the vertical center line 82 of the chamber by gravity (or other downward-directed force such as an electrostatic force). The housing 74 forming the chamber is connected through a heat-resistant horn 84 of greater height than width to a transducer 86. As in the other embodiments of the invention, the vibrating chamber is substantially fixed to a vibrating surface of the transducer.

The vibrating chamber 74 is enclosed within a furnace 88 which heats the chamber and the object therein to a high temperature, such as one at which the object becomes molten. The horn coupling 84 permits the transducer 86 to remain at a relatively low temperature which the transducer can withstand, while the chamber housing 74 and object are heated to a much higher temperature, and with the chamber being at a substantially uniform high temperature. This avoids large temperature gradients within the gaseous medium of a chamber, which can reduce the intensity of the acoustic standing wave pattern.

In the system 70 of FIG. 4, the effective height of the chamber 72 could be made adjustable by the use of a moveable bottom wall member 90 (or a top member at 76) that can be moved up and down within the chamber. This can be accomplished by using a shaft 92 to support the wall and using threads on the shaft 92 that engage a threaded hole in the horn 84. A lower end of the shaft
the object heated.

above the chamber. The housing largely cylindrical chamber forms a substantially closed chamber, and has a circular cross-section everywhere along its axis. However, the axis is curved about a point lying above the chamber. The housing that forms the largely cylindrical chamber is fixed to the surface of the transducer at each movement. An acoustic pressure sensor at the top or bottom wall can be used to control the motor to maintain resonance.

FIG. 5 illustrates another acoustic levitation system which is of largely cylindrical shape, in that it has a circular cross-section everywhere along its axis. However, the axis is curved about a point lying above the chamber. The housing that forms the largely cylindrical chamber is fixed to the surface of the transducer at each movement. An acoustic pressure sensor at the top or bottom wall can be used to control the motor to maintain resonance.

The apparatus described in claim 1 wherein: said means for moving includes a transducer having a vibrating surface, and said housing is mounted to said vibrating surface.

The apparatus described in claim 1 wherein: said chamber has a substantially uniform cross-section along most of a predetermined length dimension, and said means vibrates said chamber along said length dimension and vibrates it at a resonant frequency which produces acoustic pressure variations, at opposite reflecting walls, that are out of phase.

The apparatus described in claim 1 wherein: said chamber is of substantially parallelepiped shape, with rectangular cross-sections, said chamber has three axes X, Y, and Z, and has lengths along said axes of Lx, Ly, and Lz, the axes of said chamber are oriented at angles \( \theta_x, \theta_y, \) and \( \theta_z \) from the vertical, said angles being given by the equations:

\[
\cos \theta_x = \left[ 1 + \left( \frac{L_y}{L_x} \right)^2 + \left( \frac{L_z}{L_x} \right)^2 \right]^{-\frac{1}{2}} \\
\cos \theta_y = \left[ 1 + \left( \frac{L_z}{L_y} \right)^2 + \left( \frac{L_z}{L_y} \right)^2 \right]^{-\frac{1}{2}} \\
\cos \theta_z = \left[ 1 + \left( \frac{L_x}{L_z} \right)^2 + \left( \frac{L_x}{L_z} \right)^2 \right]^{-\frac{1}{2}}
\]

The apparatus described in claim 1 wherein: said chamber is of substantially parallelepiped shape, with rectangular cross-sections, and said means vibrates all of said chamber along an axis of vibration that subtends an angle of about 48° with both an X and a Y axis and subtends an angle of about 70° with a Z axis; and

said chamber has lengths along said axes of Lx, Ly, and Lz, and said frequency is one which produces a wavelength equal to \( L_x^2 + L_y^2 + L_z^2 \).
whereby to maintain an essentially constant position for a levitated object.

10. The apparatus described in claim 9 including:
means for heating said chamber walls to heat the entire volume within said chamber, and wherein;
said vibrating means includes a transducer spaced from said chamber and at a lower temperature than all portions of said chamber, and a horn coupling said transducer to said chamber walls to vibrate all of the walls of said chamber.

11. Apparatus for levitating an object comprising:
walls forming a chamber of largely cylindrical shape, but with the axis of the cylindrical shape being curved about an axis lying above the cylinder, and means for vibrating all the chamber walls, with the chamber in a substantially undistorted state, whereby an acoustic standing wave pattern is established within said chamber along its diameter.

12. A method for establishing an acoustic standing wave pattern within a chamber formed by a housing, comprising:
rapidly moving all of said housing back and forth with the housing in a substantially undistorted state, at a frequency which produces a standing wave pattern within said chamber, whereby to maintain an essentially constant position for a levitated object.

13. The method described in claim 12 wherein:
said step of rapidly moving comprises attaching said housing to a surface of a transducer, and energizing said transducer to vibrate said surface.

14. The method described in claim 12 wherein:
said chamber is of uniform cross-section along most of a predetermined height direction, and said step of vibrating includes vibrating said chamber along said height direction at a resonant frequency which produces acoustic pressure variation, at opposite reflecting walls, that are out of phase.