A system is described for use with acoustically levitated objects, which enables close control of rotation of the object. One system includes transducers (18, 20, 22) that propagate acoustic waves along the three dimensions (X, Y, Z) of a chamber (16) of rectangular cross section. Each transducer generates a first wave which is resonant to a corresponding chamber dimension to acoustically levitate an object, and additional higher frequency resonant wavelengths for controlling rotation of the object. The three chamber dimensions and the corresponding three levitation modes (resonant wavelengths) are all different, to avoid degeneracy, or interference, of waves with one another, that could have an effect on object rotation. Only the higher frequencies, with pairs of them (e.g. 50, 52) having the same wavelength, are utilized to control rotation, so that rotation is controlled independently of levitation and about any arbitrarily chosen axis.

11 Claims, 4 Drawing Figures
SYSTEM FOR CONTROLLED ACOUSTIC ROTATION OF OBJECTS

ORIGIN OF THE INVENTION

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, Public Law 85-568 (72 Stat. 435; 42 USC 2457).

BACKGROUND OF THE INVENTION

An object can be levitated within a rectangular chamber by propagating acoustic waves that set up a standing wave pattern, so the object is held at a pressure node (location where pressure is a minimum). The object can be stably held along three dimensions by establishing three mutually perpendicular standing wave patterns, the object gravitating to a point where pressure nodes of the three patterns intersect. Where the same wavelength is propagated along two or three dimensions (with corresponding finite air particle velocity components at the object position to apply a torque to the object), the object undergoes rotation in an amount determined upon the phase difference between the waves of the same wavelength. U.S. Pat. No. 3,882,732 by Wang et al., shows (in his FIG. 13) a chamber of square cross section with equal wavelengths along two directions, which rotates the object by controlling the relative phases of waves of the same wavelength.

While the use of a square chamber and equal wavelengths along two perpendicular directions to levitate and rotate an object, provides a simple and effective technique in some applications, its use can be limited. In high temperature environments, as where the levitated object is heated to process it, temperature gradients along the path of the acoustic waves, between the room temperature of an acoustic drive and the high temperature chamber, can produce significant phase changes in the degenerate wavelengths that results in uncontrollable rotation. Another cause of uncontrolled rotation is partial coupling of acoustic waves of the same wavelengths initially propagated in different directions, which can modify their phase relationship and lead to unanticipated object rotation. Such rotation is especially troublesome where very high sound intensities are utilized for levitation so a slight phase difference may produce a large object-rotating torque.

SUMMARY OF THE INVENTION

In accordance with one embodiment of the present invention, a system is provided for closely controlling rotation of an acoustically levitated object, which provides a high degree of object rotation control. This is accomplished basically by utilizing one set of wavelengths for levitation and a separate set for control of rotation, and by choosing the levitating wavelengths so they do not affect rotation.

In a chamber of predetermined width and length, one transducer propagates acoustic waves resonant to the width of the chamber but of two different frequencies. Another transducer propagates two different resonant acoustic waves along the length of the chamber. The chamber dimensions and the acoustic wavelengths are chosen, so that the first wavelengths from the two transducers are distinctly different to prevent them from affecting object rotation, but only to levitate the object (in conjunction with a means for levitating in a third direction). The second wavelengths from the transducers are substantially identical, so that their relative phases control rotation of the object. Acoustic energy of the two second wavelengths can be much lower than the first wavelengths that are utilized for levitation. The direction (clockwise or counter clockwise) and rate of rotation are determined by the relative phases and amplitudes of the second wavelengths. In a system with a rectangular enclosure, three transducers are utilized so that each propagates three wavelengths, to control rotation about three axes. Rotation also can be controlled in a cylindrical chamber or in a chamber of rectangular cross section but with open ends.

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.

DESCRIPTION OF THE DRAWINGS

FIG. 1 is a partially perspective view of a levitating and rotation controlling apparatus constructed in accordance with the present invention.

FIG. 2 is a graph showing the nine wavelengths propagates in the chamber of FIG. 1.

FIG. 3 is a perspective view of a system of another embodiment of the invention.

FIG. 4 is a schematic top view of a system of another embodiment of the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 illustrates a system 10 which can be utilized to acoustically levitate an object such as the sphere shown at 12 and closely control its rotation about any of three axes X, Y, and Z. The three transducers are driven by three drivers 24, 26, and 28, which produce electrical signals that are converted into acoustic waves by the transducers. In this particular application, air or other gas in the chamber is at an elevated temperature while transducer elements 18, 20, and 22 of the transducers 18-22 must be kept near room temperature. Temperature isolation is achieved by using tubes 18t, 20t, and 22t to couple each transducer element to the chamber.

Each of the drivers such as 24 includes three oscillators 30, 32, and 34, to generate three different frequencies that are all combined by a mixer-amplifier 36 that delivers the three frequencies to the transducer 18. The output of the first oscillator 30 is of relatively low frequency and high intensity, and is utilized only to levitate the object 12 (by driving it at a resonant mode of the chamber) as to maintain the object at a predetermined location along the X, axis. The other two oscillators 32, 34 generate higher resonant mode frequencies, and are utilized only for controlling rotation of the object. The first oscillators 30 of each of the three drivers are all set at considerably different frequencies to prevent interaction between them that could affect rotation of the object. When two or more frequencies (and their corresponding wavelengths) are equal, they are typically referred to as degenerate. The frequency outputs of the other two oscillators 32, 34 of each driver are intended to match certain frequency outputs of other drivers, for the purpose of creating degeneracies that can cause rotation of the object.

In one example, the chamber 16 has a width X along the X-axis of one unit such as one foot, a length along the Y axis of 1.667 times X, or in other words 1.667
feet, and a height along the Z_a axis of 0.714 times X or 0.714 feet. In order to establish a standing wave pattern, all acoustic frequencies in this chamber should be resonant to the corresponding distance across the chamber. FIG. 2 shows the relative lengths of the waves propagated by each of the three transducers 18-22 of FIG. 1. The second excited frequency of the X_a axis transducer 18 corresponds to the third harmonic acoustic mode X_3 shown at 50, which has a wavelength of 0.667X. The second excited frequency of the Y_a axis transducer 20 corresponds to the fifth harmonic acoustic mode Y_5 which also has a wavelength of 0.667X. Since the X_3 and Y_5 modes are substantially the same, a degeneracy is produced which leads to rotation of the object if the waves are not in-phase (or 180° out of phase). Such rotation caused by the X_3 and Y_5 modes, is the rotation about the Z_a axis indicated at 54 in FIG. 1.

The third frequency that the X_a axis transducer 18 produces corresponds to the seventh harmonic mode Y_7 having a wavelength of 0.286X as shown in FIG. 2. The third frequency excited along the Z_a axis corresponds to the fifth harmonic mode Z_5 which also has a wavelength of 0.286X. Thus, there is a degeneracy between the X_7 and Z_5 modes, resulting in rotation about the Y_a axis as indicated at 50 in FIG. 1. The third excited frequency along the Y_a axis corresponds to the seventh harmonic mode Y_7 along the Z_a axis which corresponds to the third harmonic mode Z_3 which has a wavelength of 0.475X which is substantially the same as the Y_7 wavelength. This produces a degeneracy that can cause rotation about the X_a axis, as indicated at 56 in FIG. 1. It may be noted that a wavelength can be within about one percent of an exact resonant mode and still efficiently produce a standing wave. The permitted deviation depends on the Q of the chamber in that mode. A typical chamber Q for a standing wave may be about 100, which means that the acoustic energy level drops to one-half the maximum attainable (at the exact resonant frequency) when the frequency deviates by one-half percent from the center resonant frequency. Thus, by utilizing three resonant wavelengths along each of the three axes of the chamber, the object is levitated in a manner that prevents the levitation wavelengths (e.g. X_1, Y_1, Z_1) from causing object rotation while other matched pairs of wavelengths (e.g. X_3 and Y_5, or X_7 and Z_5, or Y_3 and Z_5) along different directions enable control of object rotation about three mutually perpendicular axes of rotation. An arbitrary axis of rotation may be attained by simultaneously exciting the three pairs of degenerate wavelengths at appropriate intensity levels and phase shifts. It may be noted that the apparatus shown in FIG. 1 is useful primarily under a nearly zero gravity environment where transducers of only moderate intensity are used. In outer space environments, where accelerations such as 10^{-3} G may be encountered from astronauts moving around, levitation intensities of about 140 to 155 decibels may be utilized. The other frequencies utilized for rotation, may be of a much lower intensity such as 10 decibels lower than for levitation. The amount of torque applied to the object depends upon the phase difference between the two wavelengths that are degenerate, as well as their intensities. Thus, large torques can be produced at relatively moderate intensities of the degenerate modes, by utilizing large phase differences which may approach 90° for maximum torque.

The choice of the dimensions of the chamber 16 is made to enable the use of relatively low modes, with at least one mode along each direction being of different wavelength from modes along the other two directions (for levitation) and three pairs of modes (for rotation about three axes) being of the same wavelength. The particular relative dimensions and modes described in the example above is an especially simple solution to the problem of picking appropriate dimensions which lead to degenerate wavelengths at resonant modes above the fundamental, but other sets of dimensions and corresponding wavelengths can be utilized. Chamber dimensions that enable the use of relatively low modes, preferably below the tenth mode in each direction, avoid the possibility of inadvertently generating several high resonant modes simultaneously. It may be noted that since control of the relative phase difference and/or intensities of the degenerate modes controls the amount and direction of torque rather than speed of rotation, it is often desirable to provide a sensor for indicating object speed of rotation.

The separation of rotation from levitation has several advantages. In a high temperature environment wherein the tubes 18t-22t carry acoustic energy into the chamber, the large temperature gradient along a tube such as 18t makes it difficult to predict the sound velocity in the tube. Accordingly, the phase of the sound, and therefore the relative phases of the resonant modes are hard to predict accurately. By using different and therefore nondegenerate levitation frequencies, their relative phases are of no relevance to rotation. The degenerate frequencies used for rotation can be maintained at a very large phase difference, so small phase variations are of small effect, and rotation is closely controlled by the intensities at these frequencies (or zero intensity to avoid rotation). The precise axis of rotation may be chosen, which may not be aligned with any of the axes X_a', Y_a', or Z_a' by selection of the relative phase differences and/or intensities of each of the three pairs of wavelengths used for controlling rotation.

While the parallelepiped chamber 16 of FIG. 1 provides the most direct calculation of modes needed for levitation and rotation control, other chamber types can also be utilized. FIG. 3 illustrates another embodiment of the invention which is useful to control rotation of an object 80 that is supported by a converging acoustic field generated by a vibrating concave source 82 and reflected by a small reflector 84 slightly above the object, all as described in U.S. patent application Ser. No. 272,837 filed June 12, 1981. A housing 86 forming a chamber with open upper and lower ends, is utilized together with transducers 88, 90 for propagating acoustic waves in horizontal directions which are both perpendicular to the direction of the levitating force pro-
duced by the converging acoustic waves. The housing
has a rectangular cross section and the transducers
are driven at the same resonant frequency (and
wavelength), which produces finite air particle velocity
components at the position of the object to produce a
torque. Here, the only purpose of the transducers is to
create rotation of the suspended object.

The separation of the levitating and rotating acoustic
modes can be applied to acoustic chambers of non-rec-
tangular geometry. For example, in a long tube of elips-
tical cross-section, different wavelengths of low reso-
nant modes may be used to levitate an object along the
tube axis at a unique position. Higher order modes of
the same wavelength may be used to rotate the object.
In a similar manner, this method may be applied to a spheroid with radii of different lengths in three orthogo-
nal directions.

It should be noted that in order to rotate an object by
acoustic waves of the same wavelength propagated
along different directions, the pressure nodes of the two
acoustic waves preferably should occur at the same
location, and that location should be the location of the
levitated object. In the rectangular system of FIG. 1 the
acoustic waves are planar, and in that case the position
of the pressure nodes is the position where the air parti-
cles move at maximum velocity (velocity antinode) to
produce optimum rotation. The object location does
not have to be at the center of the chamber, since pres-
sure nodes can be created at various other locations.

While resonant modes can be generated by acoustic
waves travelling normal to the parallel opposite walls of
a chamber, it should be understood that other resonant
modes can be employed. For example, FIG. 4 shows a
chamber 92 of rectangular cross-section, in which an
acoustic wave 94 reflects off all four walls at an acute
angle, so that the resonant mode depends on two cham-
ber dimensions. The wave could be directed to reflect
off all six walls of a chamber of rectangular cross-ses-
tions, so the resonant mode would depend on all three
dimensions. A similar situation also can be encountered
in chambers with curved walls, such as in tubes of elipti-
tical cross-section or spheroidal chambers. It should
also be noted that rotating modes do not have to be
perpendicular to each other.

Thus, the invention provides a system for controlling
rotation of an acoustically levitated object. This is ac-
accomplished basically by utilizing non-degenerate acous-
tic modes for levitating the object to prevent the levitat-
ing wavelengths from influencing object rotation, and
by utilizing separate degenerate modes which serve to
control rotation. Such division of function is especially
useful where acoustic transducers (24-28), tubes
(18E-22) and the object to be levitated may be in a non-uniformly heated environment, so that the precise
phase relationship between degenerate wavelengths,
which may also be used for levitation purposes, may
vary independently. In a substantially parallelepiped
chamber, three wavelengths can be propagated along
each axis of the chamber, with one wavelength along
each axis utilized for levitation and distinctly different
from all other wavelengths. The other two wavelengths
along each direction are chosen to provide pairs of
degenerate waves, for controlling rotation along each
of the three axes of the chamber.

Although particular embodiments of the invention have
been described and illustrated herein, it is recog-
nized that modifications and variations may readily
occur to those skilled in the art and consequently, it is
intended that the claims be interpreted to cover such
modifications and equivalents.

What is claimed is:

1. Apparatus for levitating and controlling rotation of
an object, comprising:

means for applying acoustic energy along at least two perpendicular directions to a region which includes
the object, with the energy along a first direction
including energy of first and second wavelengths,
and with the energy along the second direction
including energy of third and fourth wavelengths,
the first and third wavelengths being different, and
the second and fourth wavelengths being substan-
tially the same and of lower intensity than the first
and third wavelengths.

2. Apparatus for levitating an object and closely con-
trolling its rotation, comprising:

walls defining a chamber having a width, length and
eight;
first transducer means for propagating acoustic
waves along the width of said chamber, including
waves of a first wavelength and also waves of a
second wavelength that is shorter than said first
wavelength and with said first and second wave-
lengths both resonant to the length of the chamber;
second transducer means for propagating acoustic
waves along the length of said chamber, including
waves of a third wavelength and also waves of a
fourth wavelength that is shorter than said third
wavelength and with said third and fourth wave-
lengths both resonant to the length of the chamber;

means for controlling the position of said object along
the height of said chamber;
said chamber width and length and said wavelengths
being chosen, so that said first and third wave-
lengths are different while said second and fourth
wavelengths are substantially the same, whereby
the first and third wavelength modes levitate the
object and the degenerate second and fourth wave-
length modes control object rotation.

3. The apparatus described in claim 2 wherein:
said waves of said first and third wavelengths have a
greater intensity than the second and fourth waves.

4. Apparatus for levitating an object and controlling
its rotation, comprising:

walls forming a substantially parallelepiped chamber
having a width, length and height;
means for propagating resonant acoustic waves in
said chamber, including waves of three different
wavelengths along the width, waves of three dif-
ferent wavelengths along the length, and waves of
three different wavelengths along the height;
a first of the wavelengths along the width, length, and
height all being considerably different, so that they
do not tend to rotate the object;
a second of the wavelengths along the width and
length being substantially the same to control rota-
tion of the object about a first axis extending along
the height;
a third wavelength along the width and a second
wavelength along the height being substantially the
same, to control rotation of the object about a
second axis extending along the length; and
a third wave along the length and a third wave-
length along the height being substantially the
same to control rotation of the object about a third
axis extending along the width.
5. The apparatus described in claim 4 wherein:
the first wavelength along the height is longer and at
a higher intensity than the second and third wave-
lengths along the height.

6. The apparatus described in claim 4 wherein:
said width, length, and height are dimensions, a sec-
ond of said dimensions being about 1.67 times a first
dimension, and a third dimension being about 0.71
times said first dimension, whereby to enable the
use of second and third wavelengths for each di-
mension for object rotation, which are of low mode
numbers.

7. The apparatus described in claim 6 wherein:
said second and third wavelengths of said first dimen-
sions are of the 3rd and 7th modes respectively, so
their wavelengths are about 0.67 and 0.29 times the
first dimension of the chamber;
the second and third wavelengths of the second di-
menion are of the 5th and 7th modes, respectively,
so their wavelengths are about 0.67 and 0.48 times
the first dimension; and
the second and third wavelengths of the third dimen-
sion are of the 3rd and 5th modes, respectively, so
their wavelengths are about 0.48 and 0.29 times the
first dimension.

8. A method for levitating and controlling rotation of
an object, comprising:
applying acoustic energy along at least two perpen-
dicular directions to a region which includes the
object, with the energy along a first direction in-
cluding energy of first and second wavelengths,
and the energy along the second direction includ-
ing energy of third and fourth wavelengths;
the first and third wavelengths being different, and
the second and fourth wavelengths being substan-
tially the same and of lower intensity than the first
and third wavelengths.

9. A method for levitating and controlling rotation of
an object, comprising:
applying acoustic energy along two perpendicular 40
directions at first and second wavelengths that are
different, to a region which includes the object, to
position the object; and
applying acoustic energy along two largely perpen-
dicular directions to said region, at third and fourth 45
wavelengths that are the same but which are each
different than said first and second wavelengths, to
control rotation of the object, said third and fourth
wavelengths being of lower intensity than said first
and second wavelengths.

10. Apparatus for levitating an object and closely
controlling its rotation, comprising:
walls defining a chamber substantially in the form of
a parallelepiped having a width, length and height;
first transducer means for propagating acoustic
waves along the width of said chamber, including
waves of a first wavelength and also waves of a
second wavelength that is shorter than said first
wavelength and with said first and second wave-
lenghts both resonant to the width of the chamber;
second transducer means for propagating acoustic
waves along the length of said chamber, including
waves of a third wavelength and also waves of a
fourth wavelength that is shorter than said third
wavelength and with said third and fourth wave-
lenghts both resonant to the length of the chamber;
and
said chamber width and length and said wavelengths
being chosen, so that said first and thirdwave-
lenghts are different while said second and fourth
wavelengths are substantially the same, whereby
the first and third wavelength modes levitate the
object and the degenerate second and fourth wave-
lenght modes control object rotation;
said first transducer means also producing waves of a
fifth wavelength along the chamber width, and
including third transducer means for propagating
resonant acoustic waves along the height of said chamber,
including waves of a sixth wavelength which is different from said first and third wave-
lenghts, and waves of a seventh wavelength that is
substantially the same as said fifth wavelength.

11. A method for levitating and controlling rotation
of an object, comprising:
applying acoustic energy along three perpendicular
directions at the walls of a substantially parallelepi-
ped enclosure which encloses the object;
the energy along each direction including three
wavelengths, with a first wavelength along each
direction being different from all wavelengths
along the other directions, and each of the other
two wavelengths along each direction being equal
to a wave length in one other direction.
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