ACOUSTIC SHAPING IN MICROGRAVITY: HIGHER ORDER SURFACE SHAPES

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ABSTRACT
Further results from microgravity flight experiments on acoustic shaping are discussed. In previous experiments, the authors showed that straight and curved walls could be formed using styrofoam and cereal pellets of arbitrary shape seeded in a sound field in a resonant chamber. The wall shapes corresponded to constant-pressure-amplitude contours of the sound field; however, the walls have multiple stable locations near the nodal planes. Low acoustic energy input found to be sufficient in microgravity. Here the observations are related to predictions of particle and flowfield behavior. For the low-order modes used here, acoustic streaming is an important factor in transporting particles through the chamber. Simulations using multiple harmonics indicates possibilities for constructing and transporting shapes inside the container. Flow visualization supports the streaming predictions. The streaming velocity corresponds to the predicted values for the measured standing wave pressure amplitude. Visualizations of nodal planes show the formation of shapes of specified curvature. G-jitter is of the order of 0.03g, comparable to the peak accelerations due to acoustic radiation force, limits wall formation and control time during each parabola. Complex shapes can be formed with a variety of materials in microgravity. Tailoring the sound field to specific shapes and materials appears to be within reach.

INTRODUCTION

Space-related business accounted for over $121B/yr in 1998 [1]. The International Space Station alone is expected to grow to an Earth-weight of over 1 million pounds by 2004 [2]. Currently, all items are shipped from Earth, with space-based operations limited to assembly: this is obviously a major constraint in mission planning. Even the Artists' Conceptions seen in today's web pages appear to be constrained by this limitation. For example, pictures of Mars exploration and Space Station construction [3] show modules bearing strong resemblance to empty rocket fuel and equipment storage tanks. The other aspect seen in these pictures is the prevalence of pressure vessels and radiation shields: both are needed for humans and human-engineered machines to survive outside the pressure/ temperature/ wavelength ranges of Earth's atmosphere.

By optimistic estimates, it costs $5,000 to lift each pound of matter to Low Earth Orbit (LEO) from the surface of the Earth. The rapid growth in space launch options, worldwide, may bring this cost down in the next decade. Even if it is brought down by a factor of 10, conventional manufacturing facilities and materials will be extremely expensive to ship to any extra-terrestrial activity. Clearly there is a need for non-contact, Flexible Manufacturing technology to enable the human exploration and development of space.

Since the early 1970s, [4] NASA has been developing technologies for Space-based materials processing. Much of this has been driven by the markets for high-purity products, and high-accuracy measurements of material properties and surface phenomena. For instance, droplet formation mechanisms can be studied precisely, and so can the surface forces of various substances, which are very difficult to measure in 1-g conditions. Non-contact positioning allows studies of materials under conditions where surface contact would contaminate or destroy the phenomena being sought. Wang [4] points out that of the electrostatic, magnetic and acoustic means of positioning studied, the acoustic offers excellent promise, because of its versatility. With gravity removed, the acoustic force is adequate to move materials of arbitrary density, regardless of their electromagnetic properties. A review of the literature shows that the most attention has been focused on precise manipulation of single drops or solid spheres using acoustic fields. The challenges have been in dealing with non-uniform temperature fields, rotation of the droplets, and achieving clean, symmetric acoustic fields devoid of unwanted harmonics and other distortions. Some work has also been reported in the analogous problem of manipulating particles suspended in liquids, where gravity is balanced by hydrostatic buoyancy.

The focus of the present effort is on constructing complex shapes from raw materials using an acoustic field. The long-term goal is to develop construction technology, where materials mined from low-gravity environments such as the moon or asteroids is used to provide the bulk of construction material for space operations. Non-contact, flexible fabrication of components, in this context, would provide an enabling technology for the human exploration of space.

Work on acoustic "levitation" has progressed since the late 19th century [5], when observations were reported of coal dust accumulating in heaps at locations corresponding to the nodes of sound fields in mine shafts. A brief survey of the patents related to acoustic positioning was given in [6]. Wang [4] summarized the

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NASA program directed at acoustic positioning. He also conducted several experiments on sub-orbital sounding rockets, where relatively long duration's of microgravity could be achieved, with motion picture cameras used to record the behavior of a few objects.

EXPERIMENTAL APPROACH

The Georgia Tech student team used an air-filled rectangular box in microgravity flight tests in 1997 and '98. The chamber was made of ½ inch plexi-glass. Four speakers were mounted flush to the sides of the chamber as seen in Figure 1. Three video cameras were mounted to the sides of the chamber to capture the response of solid particles to various sound parameters.

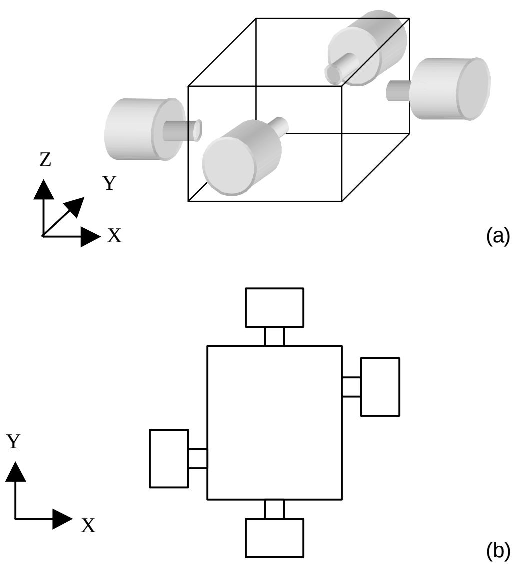


Figure 1. Chamber geometry, showing speaker location enabling modulation of x-y modes. (a) oblique view and (b) plan view

WALL FORMATION USING STYROFOAM PIECES

In the 1997 flights very good results were obtained using styrofoam pieces of arbitrary shape. They formed large walls that extended the full height of the chamber. At low amplifier gain settings (later determined to produce 150dB in the resonant chamber) they formed stable walls and did not show any rotation. All walls formed were one pellet thick. An example is shown in Figure 2.

Figure 2: Wall formation using styrofoam pellets in zero-g: Parabola #7, Flt. Test 1, April 1997. Mode: (110), see corresponding pressure field in figures 5(b)and 5(c). Snap shot from side camera located along a y=Ly/3 line, looking through side wall.

ISSUES

- The Georgia Tech Microgravity student flight team [6], as discussed above, developed Acoustic Shaping technology to form complex shapes using large numbers of solid particles in air, in a rectangular chamber. The particles used had random shape in one case (styrofoam pieces), and quasi-ellipsoidal shape in the other (Kellogg's Rice Crispies Cereal). Comparing with the bulk of the work in the literature shows some differences:
- The frequencies used in these experiments are very low: 800 to 3000Hz, as compared to 50KHz to 1MHz ultrasonic frequencies generally used (see [7]).
- The chamber dimensions are such that the modes studied are the lowest: **(100)** and up, so that details of particle behavior at various points in the standing wave are seen. Also, in this case, the acoustic streaming is expected to form only a few cells in the chamber.
- Thermal effects are negligible, since the speakers operate in the audible range.
- The power input to the speakers is relatively low (settings 3 to 7 on the volume dial of a home stereo system)
- The resonant field pressure amplitude is moderate: 150dB to 159dB.
- The particles used in the 1997 experiments had low density: styrofoam specific gravity is 0.025.

The flight test parameters for the two modes discussed here are given below:

Table 1:

Parameter	Value
Chamber dimensions (Lx,Ly,Lz)	(0.21,0.17,0.10) meters
Frequency of (100) mode	800 Hz
Frequency of (110) mode	1250 Hz

Other details of the flight tests are discussed in Ref. 6.

The 1997 experiments demonstrated that:

- The container shape did not have to be symmetric, nor the speaker positions exact. Rather than the cylindrical or cubic containers used in previous work, the student experiment used a rectangular box with non-integer dimension ratios between sides.
- Particles self-align to form walls in the sound field, rather than agglomerate around a single stable point. The single-point agglomeration had been feared based on preliminary studies of the literature on previous single-particle experiments.
- The wall shapes corresponded with high fidelity to predicted shapes from acoustic mode calculations.
- Wall shapes could be flat, or have varying radius of curvature in multiple dimensions, as predicted from basic sound field theory.

- Particle shapes could be heterogeneous, similar to crushed solid construction material.
- Low, audible-range sound energy input is adequate in microgravity to form multiple walls of either straight or curved shape: ultrasonic frequencies or high power levels are not essential.
- Varying speaker location, phase and amplitude could be used to control the behavior of particles of various sizes, shapes and densities.
- Analysis of the sound field revealed that there were substantial levels of higher-harmonic spectral content.
- Complex flow patterns were observed in the chamber.

These findings were very encouraging. To make progress towards the long-term goal, verified analytical models are needed for several aspects. These models would be the basis for computational methods to design appropriate chamber geometries and acoustic fields for given material characteristics. Conversely, knowledge of these models would guide the tradeoffs between pre-processing costs of materials, and the tailoring of the sound field for a given processing operation. To develop such models, answers are needed on the basic physical mechanisms involved.

- Why do the particles move to the stable wall locations?
- Why do they stay stable at these locations?
- Why are there multiple stable locations?
- What determines the distribution of particles between different stable locations?
- What is the effect of having multiple harmonics present?
- What is the effect of particle size and material density on the wall formation process?

Below, the current status of our understanding on each of these issues is presented.

Particle motion

In the flight tests, the sound field is set to the selected frequency and amplitude, at 1g, before the aircraft goes into the parabola. The first manifestation of the sound field effect is an organized, large-scale motion of the particles in the chamber, which cannot be explained as the effect of aircraft acceleration. Swirling motions are observed. Next, it is seen that particles "fall into line" along several surfaces. This process continues with additional particles filling in gaps in the formed walls. If there is "g-jitter" during this process, the walls move, and sometimes there is rapid motion of particles to other wall locations. The walls collapse when the aircraft pulls out of the parabola and the g-level goes up.

There are four possible explanations for the organized motion of the particles:

a. The acoustic radiation force due to the standing wave pattern in the chamber. This accelerates particles towards the pressure nodes.
b. Interaction with higher harmonics of the sound field, causing interference effects which again develop low-frequency movement.
c. The acoustic streaming effect, which generates counter-rotating pairs of vortices near the walls. Interaction between these flows at the corners of the box creates strong vortices along the edges.
d. Steady flow from the speakers themselves, a form of the "zero-mass flux" jets used in flow control.

There is evidence of each of these, and one suspects that in a large-scale facility where complex geometric shapes are sought, one must deal with each of these. In ground tests, we verified that varying phase of two speakers could move the particles in the chamber. Such controlled experiments were difficult in the 25-second duration of the flight parabolas, especially in the presence of g-jitter. The higher harmonics in the chamber are shown in Ref. 6. The 2nd and 3rd harmonics are, respectively, 10 dB and 30dB lower than the fundamental.

Steady flow from the speakers also appears unlikely at low gains, since the tests show particles accumulating at the speaker faces. This conforms to the model of particles being stable at the velocity anti-node locations, where the velocity fluctuation is maximum: the speaker faces. If there were a strong streaming flow developing from the speaker face, it would entrain the particles and drive them out.

The general expression for radiation force [7] reduces, for the case of solid particles in air [4], to:

$$F(x) = (5\pi/6)(p_1^2/\rho c^2)ka^3\sin 2kx,$$

where

- c = speed of sound
- k = wave number = $2\pi/\lambda$
- p = acoustic pressure amplitude
- ρ = air density
- λ = wavelength of acoustic wave

In the1998 flight tests, various sizes of spherical particles, of various densities, were used. Here the wall formation was not as effective as for the 1997 tests with styrofoam. The level of g-jitter, which was slightly higher than in the 1997 tests as shows later, broke up the walls soon after they were formed.

Acoustic Streaming

Ref.[8] gives a brief treatment of the phenomenon of acoustic streaming, developing it as a basic consequence of imposing acoustic velocity fluctuations on the 2-dimensional unsteady boundary layer equations. They show that the fluctuating parts of the convective terms in the momentum equation generate terms whose temporal variations are functions of ($\omega+\omega$) and ($\omega-\omega$). The former generates higher harmonics, and the latter generate steady-flow terms. We use the simple example of streaming between two parallel plates, given in [8] to study the conclusions. The expressions for the u and w- components of velocity describe a steady velocity field consisting of counter-rotating vortex pairs:

$$u = -(3\nu_o^2/16c)\sin 2kx\,[1-3(y-{}^1\!/_2 h)^2/({}^1\!/_2\,h)^2],$$
$$w = (3\nu_o^2\,k/8c)\cos 2kx\,[y-{}^1\!/_2 h-(y-{}^1\!/_2 h)^3/({}^1\!/_2\,h)^2],$$

where, $\nu_o = P_o/\rho c = 1.31$m/s
P_o = acoustic-pressure amplitude = 553 N/m^2
ρc = characteristic impedance = 412.8 rayls
k = wave number = $2\pi/\lambda$ = 14.612 m^{-1}
h = height of chamber = 0.1m

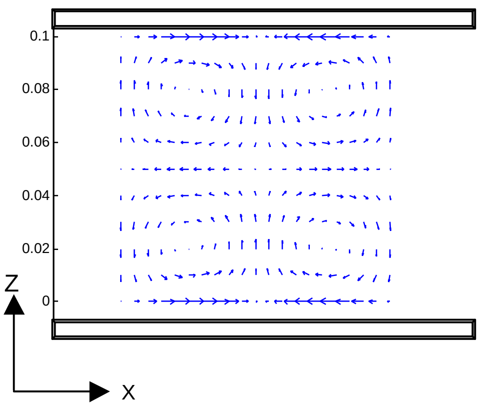


Figure 3: Streaming flow pattern in the x-z plane, computed for an 800Hz standing wave corresponding to the (100) mode in the space between two infinite walls, 0.10 m apart. Pressure amplitude is 553 Pascal's.

The spatial scales of the problem are studied for the fundamental mode of the acoustic chamber used in the present experiments. The geometry and flow patterns are given in figure [3], computed for the measured values of chamber height, h, resonant frequency of the (100) mode, (800Hz), and the measured resonant sound pressure amplitude at the pressure antinode.

This shows that the dimensions of the streaming flow are of the same order as the flow observed in the test chamber for this mode. The velocity magnitudes compare favorably with those measured. Of course the flow patterns are much more complex for the actual low-aspect ratio box than those derived for the 2-D example above, with its pair of infinite flat plates.

Given that the acoustic streaming is a plausible model for the generation of the steady flow, we can reliably estimate the variation of the mean flow velocity in the chamber with sound amplitude and frequency.

Why do particles come to rest at the stable locations?

The pressure nodes are predicted as stable points for the radiation force field, and the streaming pattern also show symmetry planes there.

Why do multiple walls form?

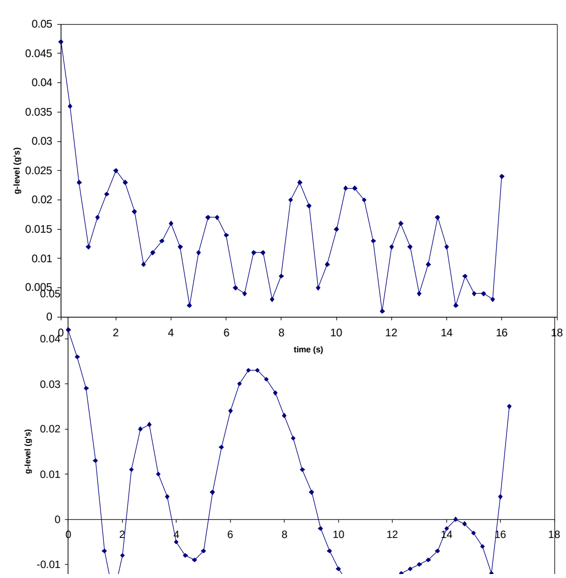
Several walls are seen to form, parallel to the node planes (pressure contours, as shown in Ref. 6). We do not have an explanation for this at present.

Effect of particle size and density

In the 1998 flight tests, most of the test particles were spherical. Spheres of various density and size were used, color-coded for visibility. Data analysis has not progressed to the point where the various parametric variations can be quantitatively measured and presented. Some guidance is obtained by considering the effect of size and density from the expression for radiation force. The acceleration is inversely proportional to the particle density. Particle size does not have any effect, according to this; however, the acceleration due to the drag is inversely proportional to the diameter. So for large particles, used in the construction industry, the drag effect should be small.

g-Jitter Effects

The level of g-jitter on the KC-135, during the microgravity flight test, had an influence on the wall formation and particle transport phenomena. Figures 4(a) and 4(b) compare g-jitter levels for various parabolas for flight tests conducted in 1997 and in 1998. These were measured by reading the g-level display from the cabin, which updated 3 times per second, from the videotape, played back in frame-stepping mode. The digitization rate is thus the same as for the display. It appears that the g-jitter in the 1998 experiments included low-frequency fluctuations of about 0.03g (Fig. 4b), while the parabolas which produced the most steady walls in 1997 (Fig. 4a) had only random, short-duration spikes of about 0.02g. The jitter has two unwanted effects. First, it causes accelerations comparable to the highest acceleration caused by acoustic radiation for styrofoam particles. For higher-density particles, the acoustic acceleration is even lower (inversely proportional to density). Thus it is much harder to form and maintain walls using particles of higher density, for the same level of g-jitter. Secondly, the low-frequency g-jitter is even more harmful, because it moves the particles by substantial distances away from the stable wall locations. The effect of g-jitter is worse in runs where complex mode shapes were being tested, including intersecting walls, where the resonant pressure amplitude, and thus the radiation force is lower. These explain much of the difference between the 1997 tests and the 1998 tests. The best short-term solution is to



perform free-float experiments, thereby reducing g-jitter by an order of magnitude, at the cost of some experimental complexity and a shorter micro-g time during each parabola.

Figure 4(a): g-jitter, 1997 Flight 1, parabola 7

Figure 4(b): g-jitter, 1998 Flight 2, parabola 23

Effect of higher-order modes

From the above, we see that analytical/numerical formulations can explain most of the particle behavior seen to-date. The formation of multiple walls near the nodal plane remains unexplained. From the 1997 data it was seen that the shapes corresponded quite closely to the unforced modal distributions of the chamber, which could be derived from the homogeneous Helmholtz equation, as given below. This concept is expanded here using simulation to observe the effects of having higher harmonics of specified amplitude along with the fundamental. The resonant sound fields in an unforced, hard-walled chamber for various combinations of fundamental and higher harmonics simulations were performed using MATLAB. Fig. 5 shows locations of pressure nodes for various combinations. These show that various surface shapes, including intersecting walls, are possible in theory. Some of these can be held stable in time.

Eigenvalue Problem

$$p = \psi(x,n)\cdot e^{-i\omega(n)t}$$

where, $\psi(x,n)$ is the eigenfuntion that satisfies the Helmholtz equation and zero (rigid) boundary conditions.

Boundary-Value-Problem

Governing Spatial component of Wave Equation:

$$[\nabla^2 + K^2(n)]\cdot\psi(x,n) = 0$$

with zero boundary conditions:

$$\nabla\psi(x,n)\cdot n_{out} = 0$$

$$\psi = X(x)\ Y(y)\ Z(z)$$

and solving the 2nd order linear differential equations:

$$X'' + K_x^2 X = 0\ ;\ Y'' + K_y^2 Y = 0\ ;\ Z'' + K_z^2 Z = 0$$

where the separation constants:

$$K_x^2 + K_y^2 + K_z^2 = K^2$$

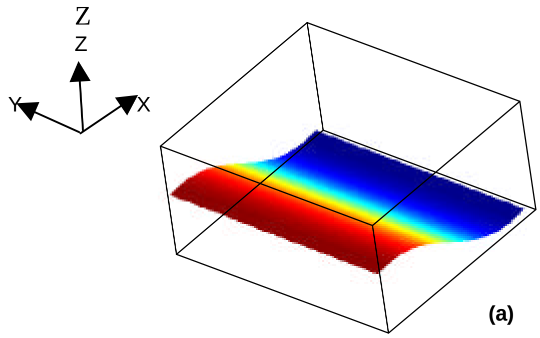
Applying the boundary conditions gives the Eigenfunction:

$$\psi(x,y,z,n) = A\cos(n_x\pi x/L_x)\cos(n_y\pi y/L_y)\cos(n_z\pi z/L_z)$$

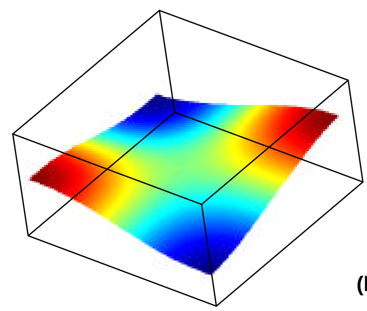
where the Eigenvalues are:

$$K^2 = \pi^2[(n_x/L_x)^2 + (n_y/L_y)^2 + (n_z/L_z)^2]$$

Applying this system of equations to our chamber dimensions and speaker settings (frequency), and assuming rigid walls and no forcing, provides us with a visual pressure profile using MATLAB. Several solutions are shown below. The following figures are simple pressure profiles that illustrate the mode shapes they can produce that vary in x and y directions, constant in z.



(a)



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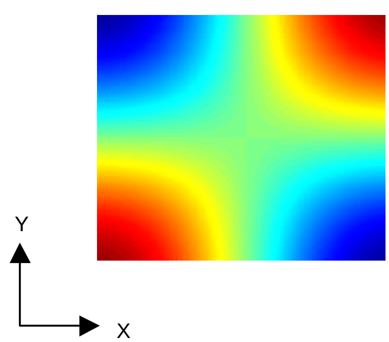
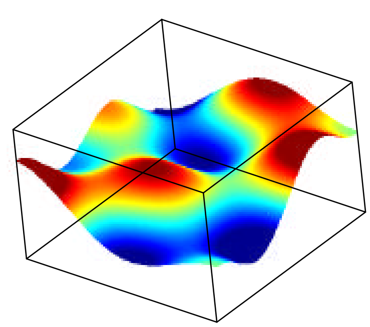


(c)



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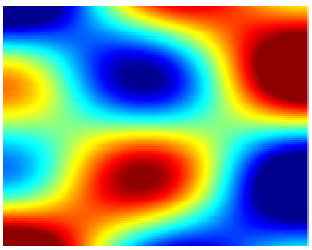
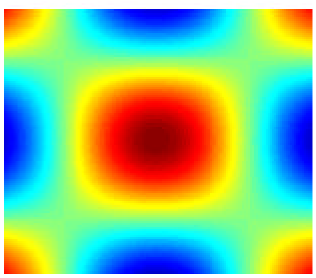


(e)



(f)

Figure 5(a) shows the (1 0 0) mode responsible for forming straight walls lying along various x locations. 5(b) is the (1 1 0) mode responsible for the walls formed in figure 2. 5(c) is the plan view of 5(b). 4(d) is a complicated (320) mode and (110) superimposed. 5(e) is its plan view illustrating the probable shape outline that would be formed. Note modes that vary in Z are not shown here due to the complexity of representation. Fig. 5(f) corresponds to a cylinder in the middle of the chamber, while 4 half cylinders at the four sides, and four ¼ cylinders at the corners. Nodal planes are denoted by the lowest gray-scales in the figures, located between peak and trough.

DISCUSSION

It has been proven through experimental demonstration, that solid walls can be formed and shaped using only standing acoustic waves. From flight tests, when we set the chamber in a **(100**) mode, Fig. 5(a), several straight walls are formed parallel to the yz-nodal plane [6]. When run in the **(110)** mode, (Fig. 5(b) and Fig.2), four curved surfaces were formed around the four corners of the box. Observing that actual surfaces are formed and have a proportional relationship to the predictions made through MATLAB simulations of the homogeneous solution, we are optimistic that higher order, complex structures are attainable, once a steady microgravity environment is achieved. Free-floating the setup during upcoming (March '99) KC-135 flight test will assist in reducing the external g-jitter effect on the shaping process. Looking beyond, the technical issues in establishing acoustic manufacturing on an orbiting Space Station appear to be within the realm of feasibility. In the near term, this might provide a solution for the replacement of panels damaged by micro-debris impact, Scaling the panel sizes upto dimensions of a few feet appears to be straightforward. This may open the door to space-based construction of future facilities, using materials mined from the lunar surface. Studies of the properties of lunar materials are given in [9].

CONCLUDING REMARKS

1. Data on particle group behavior in resonant sound fields is studied using data fromKC-135 flight test experiments, and from ground experiments.
2. Complex shapes are formed with a variety of materials in microgravity. Despite a moderate particle loading in the chamber, chamber acoustic performance is not significantly degraded.
3. Symmetric, curved shapes can be generated.
4. The dependence of the particle behavior on particle density appears to be consistent with predictions of radiation force and streaming, and with measurements of the sound pressure level
5. The formation of multiple walls remains unexplained.
6. Acoustic streaming appears to be a major factor in transporting particles to the stable locations.
7. The peak acceleration levels due to the acoustic radiation are comparable in level to the g-jitter in KC-135 experiments; however, if the jitter consists of short spikes, the walls are still formed.

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