AIAA Paper 00-1020

ACOUSTIC SHAPING: APPLICATION TO SPACE BASED CONSTRUCTION

S. Wanis, C. Matos, N. Komerath
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

ABSTRACT

Previous work has shown the formation of solid particles into thin walls of specified shape using a resonant acoustic field in microgravity. Here these results are summarized, and extended to study the qualitative effects of liquid addition and melting/ solidification in the acoustic field. Pure liquid forms into sheets, even in the 1-g environment, due to the static pressure differences in the resonant chamber; however these sheets exhibit instabilities, and shatter into droplets. Stable thin walls are formed from liquid with suspended powder in 1-g. With some adjustment of the frequency, the use of processes involving heating, cooling and phase changes are seen to be feasible. The implications of these findings to non-contact manufacturing and construction in space are discussed.

INTRODUCTION

The focus of this effort is on constructing complex shapes from raw materials using an acoustic field. A long-term goal is to develop construction technology, where materials obtained from low-gravity environments such as the moon or asteroids are 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 and habitation in space.

Today the cost of launching payloads into low Earth orbit ranges from $6000 to $25000 per kilogram. Even if this cost comes down to $4000 per kilogram, as projected today, most concepts for developing industry in Space remain infeasible. Space-based manufacturing techniques, using materials derived from low-gravity environments and supplying space-based markets, would provide a long-term solution to this problem. Acoustic shaping deals with the issue of manufacturing components in microgravity with minimal requirements for heavy machinery.

Experiments to-date by our group have demonstrated that stable walls of specified shape can be formed, along or parallel to nodal surfaces of a resonant acoustic field, in micro-gravity. Results from flight tests and ground tests show that the concept of acoustic shaping can be applied to various types of materials, including solid spheres, low-density foam particles, porous organic particles, micron-scale powder, hollow aluminum spheres, and hollow aluminum oxide spheres. Most recently, experiments mixing liquids into the process have shown encouraging results.

BACKGROUND

In Ref. 1, the basic idea of forming complex surfaces in microgravity was studied using KC-135 flight test results. A team of undergraduate students from our laboratory used an air-filled rectangular box in microgravity flight tests in 1997, '98 and '99. The chamber is made of ½ inch plexi-glass. For the '99 flight test, only two out of the previous four speakers, were used. As seen in Figure 1 below, the two speakers were mounted to the sides of the chamber, the speaker diaphragms being recessed in small cavities. Three video cameras were mounted to the sides of the chamber to capture the response of solid particles to various sound fields. The chamber was designed to have non-equal sides. Rotation of the solid particles was not a desired feature. This also allows production of elliptical surfaces.

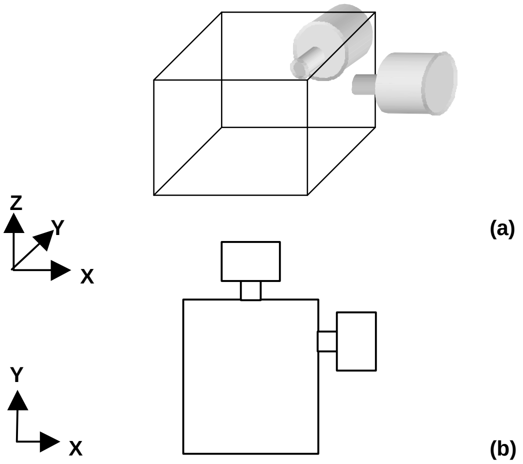

Figure 1. Schematic of the current experimental setup. (a) Oblique view; (b) Plan view.

Table 1: Chamber parameters

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

Figure 2 shows typical wall formation, using styrofoam particles in the 110-mode of the rectangular chamber. The sound used was in the audible range, so that the modes were well resolved. The input power level was on the order of 25 watts, though the resonant sound field reached amplitude of over 157 dB. The correlation between measured surface shapes and the mode shapes of the sound field was quantified. The result is shown in Fig. 2, where it is seen that particles align themselves along discrete surfaces parallel or concentric with the nodes of the predicted sound field, as shown in the planview in Fig. 2. Spectral analysis of the sound field showed that there were substantial levels of harmonic excitation, which would explain the multiple surfaces. In Ref. 2, the physics of the phenomenon was studied, and it was shown that both the radiation force and the acoustic streaming are important. The streaming convects the particles around the chamber, and the radiation force holds them in stable positions. The behavior of given spherical particles is predictable using these relations. The streaming field was shown to conform qualitatively to predictions for a 2-D geometry, and the magnitude of the streaming velocity conformed to simple predictions [2].

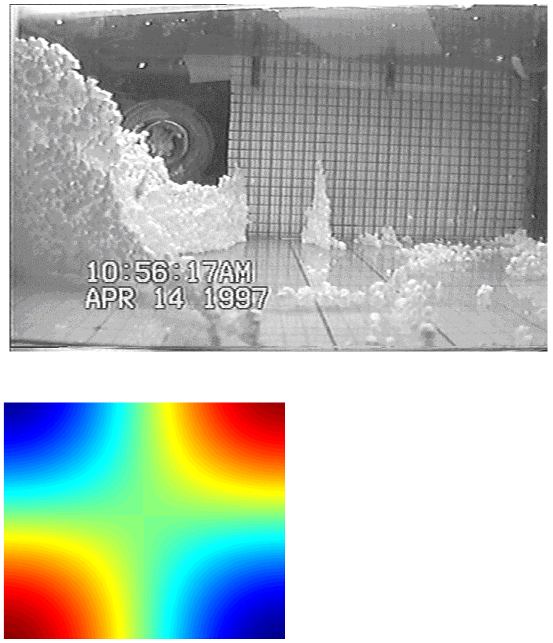

Figure 2. Side view of dry styrofoam pellets in a (110) mode, and the corresponding pressure contours in plan view.

In flights on the KC-135 aircraft, substantial levels of g-jitter were encountered, during the 25-second intervals of microgravity. The amplitude of the g-jitter is in the range of 0.03g. The crucial role of the frequency content of g-jitter was shown by comparison with flight records, confirming that low-frequency g-jitter was disastrous to the wall-formation, while high-frequency jitter was tolerable. This was explained [2], by the displacement of the particles from stable wall locations due to g-jitter, and the acceleration needed to bring them back to the stable locations.

NEW EXPERIMENTAL RESULTS

The experiments are conducted in the above-described hard walled plexiglass chamber with compression drivers. Suitable particles are placed in the chamber prior to setting up the field.

The speakers are driven at one of the normal modes of the chamber, pre-determined in simulations and refined in ground tests. This has been a source of imperfection in the flights because of temperature changes occurring between the ground test and the flight. It is assumed that the harmonic levels are increased by this mismatch. In microgravity, the acoustic streaming set up by the interaction between the standing wave in the chamber, and the wall boundary layers, transports the suspended particles around the chamber. The particles are accelerated towards the nodal planes by the acoustic radiation force, and accumulate along single-particle-thick walls there, unless displaced by g-jitter. The geometry of these walls is easily predicted, to first order, using the solution of the Helmholtz equation, as seen in Fig. 2.

The implications of the roles of the radiation force, the streaming and the g-jitter are interesting. In the space environment, where the g-jitter level can be brought to micro-g's, a very small restoring radiation force will be adequate to hold the particles in position for extended periods, so that the long-duration acoustic power requirement is minimized. This suggests that the problems of heat removal and power requirements for space-based acoustic shaping on a large scale are manageable.

Hollow-Sphere Construction Material

In 1999 flight tests, free-float tests were used to show that realistic space-construction materials such as hollow aluminum spheres (courtesy of Dr. R. Grugel, USRA), used in sintering processes, and 3mm diameter hollow aluminum oxide spheres (courtesy of Prof. Wang of GT's Materials Science School) for heat shields, do conform to wall-formation predictions. An example is shown in Fig. 3. The shiny, smaller spheres are of metallic aluminum, while the larger white spheres are of aluminum oxide. The aluminum spheres are the raw materials for sintering processes where the surfaces of the spheres would be heated to melting point under pressure in a mold, and then cooled, so that the spheres are bound to each other in a rigid matrix, while maintaining an extremely low material density because they are hollow. Here, single-particle thick walls are seen to form. By allowing walls to form along higher-harmonic surfaces, it would be possible to generate multiple walls, and to hold them in place while they are heated and cooled in microgravity, thereby forming solid shapes without molds. The wall dislocation shown is due to a sudden movement of the chamber during the free-float test.

Figure 3. Aluminum Oxide spheres forming walls in '99 microgravity flight test. Note the fluctuating g-level causing the wall to shift.

Fine Powder

Chalk powder, with grain size in the micron range, was also seen to form into solid wall shapes. Here the diameter is orders of magnitude smaller, and the particle motion is more influenced by the streaming flow. However, such powder shows promise of enabling formation of circular pipes in microgravity, forming walls of appreciable height even in the 1-g environment. In microgravity flight experiments, the powder has the obvious disadvantage of adhering to walls and rendering them opaque. Better results were obtained when the powder was mixed with the hollow spheres, typical of a configuration where powder-sintering processes would be conducted.

Addition of Liquids in the 1-g environment

The addition of liquids was expected to pose problems due to the dominance of surface tension. Colored water was injected through a needle into the empty chamber with the field on. The interaction of the water with the field was recorded on tape. A second experiment entailed adding the solid grains to the shallow (about 1-cm) water level in the chamber. This was to observe the effect of "wetted" solid grains (Aluminum oxide and styrofoam) both on the formation process and the field. As the water level was injected through the needle tip it did not seem to be affected by the field. The flow rate of the water was reduced to a minimum, where the water was dripping into the chamber, apparently unaffected by the sound field. As the water level built up in the chamber to a height of about 1-cm, the needle was removed and the SPL varied. Beyond a threshold SPL, the water formed into a very thin sheet, 2 cm high, but the sheet was highly unstable. The sheet showed cantilever-mode oscillations, with a continuous spray of droplets ejected from the top free edge. The run time for such experiments was shorter than the usual solid grain case since the spraying water would eventually cover up the interior of the chamber and reduce visibility.

Wetted Solid experiments–Ground Tests

Aluminum oxide spheres were added to the chamber containing 1 cm of water. Walls were formed according to predictions even in the 1-g environment. Due to the static pressure difference in the nodal planes, walls over 7 cm high were formed, as seen in Figs. 4 and 5. This is 70% of the chamber height. The only comparable heights achieved were during microgravity flight test.

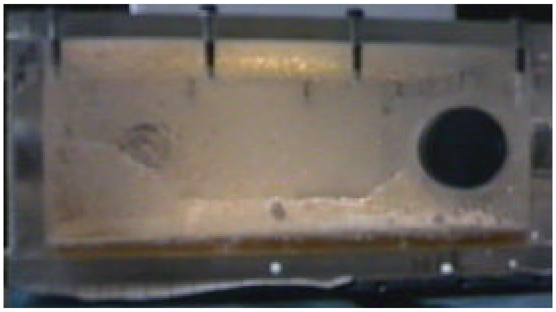

Figure 4. Ground test. Wetted Aluminum Oxide spheres and styrofoam pellets. Field corresponds to the (010) mode, 1030 Hz

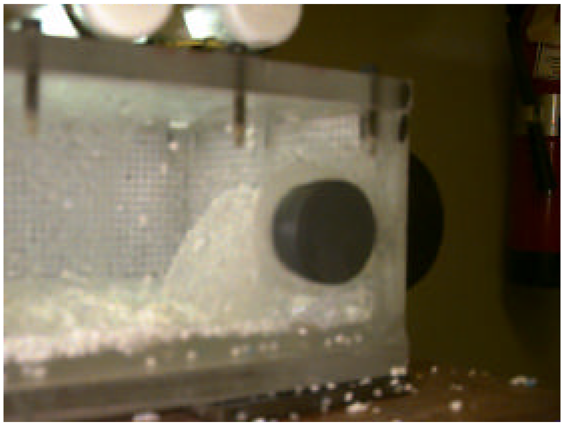

Figure 5. Ground test. Wetter aluminum oxide and styrofoam. Field corresponds to (110) mode, 1250 Hz. Note the wall height about 7 cm.

Chemical Hardening

The liquid addition provided a repeatable method for running acoustic shaping experiments in the 1-g environment. This was used to test other techniques applicable to manufacturing. The most successful was the organic polymer Agarose, which is usually used to grow bacteria, separate DNA and various other chemistry applications. Agarose, an AGAR derivative which comes from seaweed, starts out as a powder and then when mixed in water at around 60^{o}C forms a runny adhesive. If left at room temperature, it would form long chains of carbon that would be gel-like in structure and be shaped according to the container it is placed in before hardening. In our setup, a suitable grain was placed in the warm Agarose mixture, to give it strength upon formation. Knowing that the acoustic shaper produces single particle thickness surfaces, it was foreseen that if no strengthening grain was inserted into the Agarose mixture, the formed surface would collapse after formation due to its soft gel-like structure. Therefore, 1.5 mm diameter plastic orange spheres were used as the grain in the first experiment. The hardened wall is shown in Fig. 6. Note that the thickness of the wall depends on the grain diameter.

Figure 6. T-section piece hardened in an acoustic field in 1-g experiments.

Shaping in a changing temperature field

The Agarose wall formation process introduced temperature gradients in the acoustic chamber. This was accounted for by first obtaining an estimate of the frequency needed to produce the (1 1 0) mode at 60^{o}C, from the MATLAB code. The chamber was warmed up by adding a cup of water at 60^{o}C then the estimate frequency was used to drive the chamber. Scanning in tens of Hz the resonant frequency was found. The chamber was then drained out and the Agarose with the grain added. High Sound Pressure Level's were required to initially get the walls to form. Once that was attained, the speaker gain was lowered to eliminate splashing and vibration of the wall (flutter). Note that the penalty was a reduction in the wall height. As the experiment was running, the frequency was lowered in steps of 1 Hz to account for the variation in speed of sound, and thus maintain resonance as the Agarose mixture and its surroundings cooled. The SPL (gain) was also lowered with time in order to save the speakers. This did not affect the wall formation since by that time it had taken shape/form. The sound field was left on to act as a guide for the wall to harden. The actual time for the wall to form and become independent of the sound field has not yet been determined but is estimated at one minute.

MANUFACTURING ISSUES

To produce desired shapes of interest to the space manufacturer, we will need a numerical code that will enable a drawing produced by the manufacturer to couple with the acoustic solver to output the frequency needed to produce that object. From the pressure contours above, it is clear the position of the drivers is important. For complicated surfaces, requiring a higher order geometrical chamber, a numerical acoustics code would have to be designed to solve the wave equation.

Possible Products

The results of the previous three microgravity flight tests and several ground tests show good prospects for producing flat and curved panels. Materials such as pulverized solids and binder liquids under non-contact, flexible, and automated manufacturing processes can be undertaken in a space-based facility. The shapes are appropriate for fuel tanks, heat shields, greenhouses, habitats, and plumbing. For more on the preliminary economic study of such a space-based construction facility see Ref. 3

CONCLUSIONS

Continuing experiments with acoustics shaping have demonstrated that:

1. In micro-gravity, solid particles in a resonant chamber occupy stable surfaces parallel to nodal planes.
2. The surface shapes conform to predicted natural response of the chamber.
3. Symmetric, curved, and complex shapes are formed using higher-order modes.
4. The formation of stable, intersecting walls is predicted for combinations of harmonics.
5. By adjusting phase between drivers, shapes and locations can be continuously controlled.
6. Moderate particle loading in the chamber does not degrade acoustic performance.
7. Acoustic streaming transports particles to the stable surfaces.
8. Increased sound pressure amplitude increases the chaos level of the streaming flow.

9. Measurements of the velocity field in the chamber agree with the order of magnitude of the streaming flow predicted for a resonant longitudinal model between infinite parallel walls.
10. The effect of g-jitter depends on its frequency content, with high-frequency jitter being less harmful than low-frequency jitter.
11. Powder of micron size range is usable for wall formation when mixed with larger granular material.
12. Liquids in 1-g form into thin but unstable sheets at the nodal surfaces.
13. Liquids with suspended solids form into large walls in 1-g, indicating the magnitude of the static pressure difference at the nodal surfaces.
14. Chemical hardening of a T-shaped object formed by acoustic shaping has been demonstrated.
15. Temperature effects on the resonant field have been shown to be compensated by varying the excitation frequency.

REFERENCES

1. Wanis, S., Akovenko, J., Cofer, T., Ames, R., Komerath, N., "Acoustic Shaping in Microgravity". AIAA Paper 98-1065, 36th Aerospace Sciences Meeting, Reno, NV January 1998
2. Wanis, S., Komerath, N.M., Sercovich, A., "Acoustic Shaping in Microgravity: Higher Order Surface Shapes". AIAA Paper 99-0954, 37th Aerospace Sciences Meeting, Reno, NV, January 1999.
3. Matos. C., Wanis, S., Coker, A., Hausaman, J., Changeau, D., Ames, R., Tan, X.Y., Komerath, N.M., "Acoustic Shaping Inc. , Leaders in Space-Based Construction". Final Report by the Georgia Tech team to the 1999 NASA Means Business Program. Aerospace Digital Library, http://www.ae.gatech.edu/research/windtunnel/aclev/asihome.html