Acoustic Shaping in Microgravity: 3 years of flight tests

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Abstract

This paper summarizes 3 years of participation in the NASA Reduced-Gravity Flight Opportunities program. The Acoustic Shaping project was started by a team of AE sophomores in 1996. Results from the project have demonstrated the feasibility of forming complex and useful shapes in microgravity from pulverized material using sound waves, and correlated the shapes to mathematical predictions. In this paper, the genesis and evolution of the program are discussed, focusing on the process of conducting the program, issues of academic credit and technology transfer, and the impact of the program on the culture of extra-curricular participation in the School.

I. Introduction

This paper reports on a project where the synergy between research, cross-level teams in courses, and undergraduate participation in projects, has paid major dividends. The discussion is narrative, but we hope to show the educational concepts that were used in the project, and the lessons learned therefrom. In late 1996, a team of 4 Georgia Tech sophomores discovered the new NASA Reduced -Gravity Student Flight Opportunities program[1], and wanted a scientific idea to get themselves on NASA's KC-135 Microgravity Flight Laboratory[2]. The experiment had to be simple, safe and cheap. The idea had to be clear enough to explain to journalists and sophomores. It had to work, first-time, in a flying Science Fair full of airsick undergraduates.

Three years later, we are in the unique position of having the flight test proof of a technical concept, ahead of the tools needed to make accurate predictions. Through this program, we have demonstrated the feasibility of forming complex and useful shapes in microgravity from pulverized material using sound waves, and correlated the shapes to mathematical predictions. The technical results have been summarized in 3 Technical Papers [3-5] at the annual Aerospace Sciences Meetings of the American Institute of Aeronautics and Astronautics, and have led to a much more ambitious project to develop the technology into a future space-based business [6], as the nucleus of a space-based construction industry. In this paper, the genesis and evolution of the program are discussed. The emphasis is on the process of conducting the program. Issues of academic credit and technology transfer, and the impact of the program on the culture of extra-curricular participation in the School, are discussed.

II. Basics of the technology

The idea of Acoustic Shaping is simple. Sound waves exert some force on particles suspended in a fluid. In a resonating chamber, where the sound intensity varies with position, the interaction between the incident and scattered sound produces a net force on the particles. With gravity removed, this force is enough to move the particles. In a reverberating container[4], (Fig. 1), solid particles are moved towards the nodes of the sound field[7]. By driving different natural frequencies, we can generate nodal planes of various shapes. If the particles can be held in place long enough, either phase-change or chemical reactions can be used to form hard panels, just as if they were formed over solid molds. Bulky pieces needed for space stations and habitats could be built using low-grade materials such as lunar dust or regolith, without shipping heavy machine tools, dies and molds from earth. A space-based construction industry would become viable.

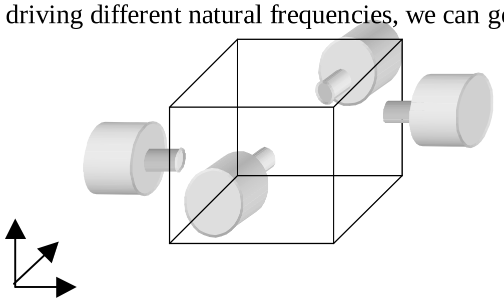


Figure 1. Chamber geometry, showing speakers exciting x-y modes. From Wanis et al, 1999 [4].

III. Project Process

a. Initiation

The first year's project began with a phone call from the student team leader to his faculty advisor, asking for supervision on a proposal to NASA. The students were asked to find out about NASA's interests in microgravity (with an assumed 50% probability that that would be the last heard about the matter).. Two days later, the students' rate of progress had decided the issue in their favor. The topic of acoustic levitation/ positioning was selected as one where a relatively harmless experiment could be designed, with a passing knowledge of acoustics and fluid mechanics. Acoustic positioning deals with moving one or a few particles to the stable points in a resonant sound field; we decided to see if this idea could be extended to form entire surfaces. The proposal was written by the student team, of whom 2 were Co-ops at Delta Air Lines, and one a Co-op at NASA Langley, and e-mailed for editing to the advisor. With little time available (a usual feature of most undergraduate initiatives, probably learnt from the homework-assignment habits of their teachers), the proposal was done efficiently and mailed off on time. The selection announcement came in late December. The preparation for the flight tests in early April had to be accomplished in an academic quarter.

b. Recruiting a journalist flyer

A major requirement of the program was that the team select a professional journalist to fly with them. With the help of the Space Grant Consortium and the Institute's Media Relations Office, Mr. Kevin Salwen of the Wall Street Journal was enlisted in the project. The keen interest taken by Mr. Salwen helped to focus the project greatly, and kept the preparations on schedule.

c. Technical Assistance

The student team was shown how and where to go about conducting a thorough literature survey on what had been done related to acoustic levitation and positioning. This search turned up over a hundred Patents, and a large number of technical papers[3]. The abstracts of all these were read, and several contacts were initiated with authors and researchers in the field. The search showed that the idea of forming whole walls, and the behavior of large numbers of arbitrarily shaped particles, remained unknown, as did the effects of using audible-frequency sound sources of relatively low power. In this phase, obviously, the advisor had to play a major role in summarizing for the students the findings from the research literature, in terms intelligible to them. The practice of searching the patent proved invaluable in introducing students to the evolution of technology and its systematic documentation.

The student flight team consisted entirely of sophomores, who had not taken any classes in aerospace engineering. To perform the needed ground-based investigations of the technology, it was essential to have more experienced help. This came from two sources:

(i) The graduate students in our Experimental Aerodynamics Group (EAG), who in 1996 had taken an advanced research experiment to 3 government and industrial facilities and thus had much expertise to provide on preparing for off-site experiments.

(ii) The seniors and graduate students who signed up for the second author's Advanced Flow Diagnostics Course[8]. Two of the 4 projects in this team-based course focused on different aspects of the acoustic shaping experiment: these students worked closely with the sophomore flight team, and one of the students also won (from NASA) the opportunity to fly at the end of the flight test program.

d. Training

Following the practice developed for off-site projects, an Experiment Manual was developed as a live document on the school's server (we were too new to the Internet to use it as a tool in undergraduate work at the time). All the information that we had found about the project was placed in this document, with references to computational tools, data files etc. as appropriate. A list of "Items to be Done" was posted and updated daily, and responsibility was assigned to various team members. The discipline needed to keep this up-to-date required the advisor's attention on an almost-daily basis. A general observation about this experience is that some of the seniors (in the Diagnostics class) had far more difficulty with this discipline than the sophomores did. Some of the senior students, who had not participated in similar projects during their years in college, also had severe difficulty with the concept of getting things done by promised deadlines, and not procrastinating solvable problems. The challenge in team project courses is to get everyone to contribute and do their jobs, rather than ignore or exempt any team member. In the final analysis, everyone succeeded. A few may have suffered bruises to their egos. This process requires intense, careful attention from the faculty advisor, remembering that the students are doing sophisticated, open-ended experimental projects for the first time, with an inflexible flight test deadline. The conflict of interest between the flight test schedule and the learning of the students must be resolved. NASA required a hazard evaluation to be written for the experiment, and this too required the advisor to visualize things that could go wrong and prove that the experiment would not pose danger to anyone under those circumstances.

The student team trained to operate their experiment under simulated conditions (equipment laid out in the right geometry). The frequency and amplitude of the sound had to be adjusted manually for each of the runs: this was a time-critical operation. A voltmeter with a sine wave was used to time the procedure against the g-variation of the parabolic flight segments. The actual flight environment can be gauged from Figure 2, where the g-indicator is the red lettering above the oxygen bottles, background left upper corner.

e. Flight Experiment

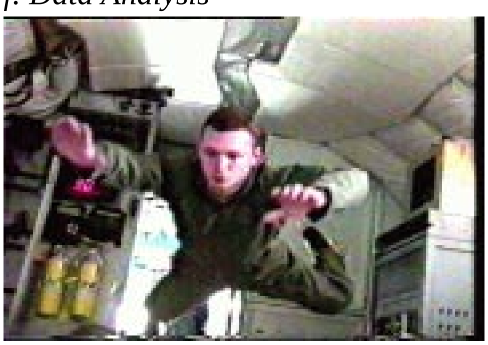
For the flight test trip to Houston, we sent a senior from the Flow Diagnostics course to help and to exert a mature presence. All 5 team members managed to get the opportunity to fly. The advisor was present only the evening before, and the day of the first flight.

Figure 2: Ron Sostaric and Andres Sercovich (with the cap) adjust settings. Flight No. 2, April 1997.

The uncertainties before the 1997 flight test were numerous. Previous work on Acoustic Positioning [surveyed in Wanis et al[3]] had shown that a single particle would move to the point of lowest potential in the chamber. Little was known about the behavior of large groups of particles. Would the particles form thin walls, or just clump around one most-stable point? Would they move in an organized manner, and if so would they stop at these planes? Would they stick to the chamber sides? Would the walls be destroyed upon formation, because the sound field would be modified by the presence of the walls, so that a steady-state solution was not possible? These questions had to wait for the microgravity flight. The students displayed more confidence than the faculty advisor felt, and followed the trained procedures exactly. As the aircraft went into the first of its 40 parabolas, the walls actually formed "as predicted", and the students forgot all about motion sickness and remained focused on their job. Figure 3 shows an example of wall formation. Styrofoam particles of random shape formed continuous walls, both straight and curved, inside the chamber. Similar results were obtained using heavier porous particles: of Kellogg's Rice Krispies Cereal. Walls were 1-particle thick in most places. Gaps were filled by arriving particles.

Figure 2: Styrofoam walls in microgravity: 110 mode, 1250 Hz. From Wanis et al, 1998[3].

f. Data Analysis



The toughest part of the microgravity flight program is to get the students to analyze the data after the emotional high of the flight experiments. This was accomplished, and a paper was written for the AIAA Aerospace Sciences Meeting. In between, there were several presentations to visitors and the School Advisory Board.

Figure 3 Tairon Cofer, GTAE Class of '99, relaxes on the KC-135 in April '97, after his experiments

g. Year 2: Exploring the Parameter Space

For the 1998 flight experiments, we proposed to obtain data over a wide range of parameters. The team had only one change from the previous year, and this project went smoothly, with minimal expenditure of time from the advisor. A pair of EAG graduate students, who were visiting Houston to give a research project presentation to the X-38 group at Johnson Space Center, stood by to help the flight team if needed. The flight results were much more complex than we had expected, and the initial procedures for data analysis proved inadequate. The enthusiasm level for data analysis was accordingly lower. The reasons for the complexity of results became clear when the theoretical analysis advanced in preparing to write the AIAA paper for the Aerospace Sciences meeting of January 1999[4]: the influence of the time scale of g-jitter on the wall formation was understood then.

h. Year 3: Evolution & Expansion

The 1999 team had only two members with prior flight experience. One of the new team members, a flight instructor at the Georgia Tech Flying Club, became indisposed and was disqualified by NASA on medical grounds, a great disappointment to a student who had done excellent work on the project all year. The experiment included a free-float segment, where cleaner microgravity was available for a short period, to test the formation of walls using realistic space-age materials such as hollow aluminum spheres and hollow aluminum oxide spheres.

A second team from our school also entered the program, with one of the 1998 flight team members being a non-flying technical expert on that team. They developed an experiment on the effect of acoustic fields on liquid behavior. The teams appear to have collaborated well and helped each other, the primary means of communication with both teams at Houston being a web page developed by the new team with photos of each day's activities.

III. Academics

a. Course Credit and Informal Learning

The participants in this project are offered the opportunity to sign up for Special Problems credit using AE2900, 3900 and 4900 credit, as appropriate. Others participate through the Flow Diagnostics/ Flow Control courses. The facilities made available to the students in this project draw out their skills in using MATLAB, AutoCAD and other tools that they learn in other courses. They take the initiative to discuss their project with many of their teachers in other courses, across the Institute. Their discussions with friends have brought many novel ideas into the project, such as the selection of materials and binders from the Materials Engineering, Biotechnology and Chemical Engineering research labs. In this respect, the absence of a formal funded research project has been a good point: it removed the barriers of "publication secrecy" and turned the project into a student-centered meeting place where people would freely exchange ideas.

b. Concepts and skills introduced

Table 1: List of Concepts learned through the Acoustic Shaping Project

Concept	**Usual place in curriculum**	**How learned**
Resonance	Junior	Calculation and observation of voltmeter readings & sound level
Acoustic modes of a container	Junior	Calculation, observations
Shop drawings	-	Experience of dealing with shop personnel
Scheduling	Senior	Project scheduling for proposal, equipment purchasing, machine shop fabrication experience, flight test preparation
Team formation	Senior	Active learning; meetings
Teamwork	Senior	Active learning; observing graduate students
Learning across disciplines	Senior elective/graduate	Graduate students;
Literature Survey		Internet & library searches
Patent Search		Library search
Testing for safety	Graduate	Hazard evaluation document; devising tests for each uncertainty
Reducing procedures to timing practice	Graduate	Flight test preparation
Calibration	Junior	Flight test preparation
Risk assessment	graduate	Hazard evaluation document; meetings
Sound measurement	Senior elective	Using research equipment; from graduate students
Video use for experimentation	Senior elective	From graduate students
Preparing a proposal	Graduate	Advisor's guidance
Data Acquisition	Senior elective	Senior elective course; graduate students
Digital Signal Processing to get sound spectra	Senior elective/ Graduate	Graduate students; advisor
Presentations	Senior	Presentations to School Advisory Board, K-12 visitors
Business trip	Senior	Trip planning, from graduate students
Particle drag estimation	Junior	Calculation of drag of particles with various sizes
Flow visualization	Junior/senior	Using video; from grad. Students
Comparing theoretical model with measurements	Graduate	Mode shape prediction vs. measured frequencies of highest amplitude

Writing papers for professional conferences	Graduate	AIAA Papers each year. From Advisor
Conference presentation	Graduate	AIAA Paper presentation.
Advancing project to application	---	Currently underway with NMB program

The presentations made, dealing with this project, and the web resources developed from the project, are listed in Refs. [10 - 12]

IV. Research and Business

The initial motivation of the student team was certainly to get a chance to fly on the Vomit Comet, and that continues to be a very strong motivator. As the team matured, their interests have broadened into other aspects as well. The idea of using Acoustic Shaping as a space-based construction technology, has focused the thinking on the project. The body of flight test results and simple analytical tools has provided the means to think of the technical barriers to be overcome, and the ideas to be tested. Our participation in the NASA Means Business (NMB) program[9] in 1998-99 (and, we hope, in 2000 and beyond) has greatly expanded the perspective of the team. This gave us the opportunity and motivation to think clearly about the technical process of going to space and proving the technology to the point where several specific products could be built. It also provided the framework to analyze the costs and business potential of the technology. This project is discussed in Ref. 13, elsewhere in these Proceedings.

V. Concluding remarks

In this paper, the participation of a student team in the NASA Reduced Gravity Student Flight Opportunities Program is summarized, over a 3-year period. This program has taken the students through a range of unique experiences while still being undergraduates. The concept of Acoustic Shaping has been taken from exploratory experiments to understanding the theoretical issues and parametric behavior, and to developing business ideas. The process of preparing for such a program and evolving and expanding it through 3 years, is summarized. The program has served to get students excited about the Space program, and has turned them into very capable and experienced engineers.

VI. Bibliography

1. Day, D.E., Ray, C.S., "Research on Containerless Melts in Space," In "Opportunities for Academic Research in a Low-Gravity Environment", edited by George A. Hazelrigg and Joseph M. Reynolds, Progress in Astronautics and Aeronautics Volume 108., p. 165-192.
2. NASA Reduced Gravity Flight Opportunities for Undergraduates, URL: http://www.tsgc.utexas.edu/floatn/
3. Wanis et al [1998]: Wanis, S., Akovenko, J., Cofer, T.,Ames, R.G., Komerath, N.M., "Acoustic Shaping in Microgravity". AIAA Paper 98-1065, 36th Aerospace Sciences Meeting, Reno, NV, January 1998.
4. Wanis et al [1999]: Wanis, S., Sercovich, A., Komerath, N.M., "Acoustic Shaping in Microgravity: Higher Order Modes". AIAA Paper 99-0954, 37th Aerospace Sciences Meeting, Reno, Nevada, January 1999. URL: http://www.ae.gatech.edu/research/windtunnel/aclev/final990954.pdf
5. Wanis, S., Matos, C.A, Komerath, N.M., "Acoustic Shaping in Microgravity: Technology for Space-Based Construction. AIAA Paper 00-1020, Reno, Nevada, January 2000.

6. The NASA Means Business Program: Web Page of the Georgia Tech team. URL: http://www.ae.gatech.edu/research/windtunnel/nmb/nmbhome.html
7. Pierce, A. D., "Acoustics" McGraw-Hill, 1980.
8. Smith, M.J., Komerath, N.M., "Learning More From Classtime: Technology Enhancement in the Classroom". Submitted to the ASEE 2000 National Meeting, Session 1602, June 2000
9. Web Page of the Georgia Tech Acoustic Shaping Project: http://www.ae.gatech.edu/research/windtunnel/aclev/aclhome.html
10. Web Page of the Georgia Tech Reduced Gravity team on liquid behavior: URL: http://www.ae.gatech.edu/~gravity/
11. Salwen, K., "Did Armstrong Turn This Shade of Green on His First Flight? Wall Street Journal, Wednesday, April 16 , 1997, page A-1.
12. Wanis, S., Cofer, T., Sercovich, A., "Acoustic Shaping in Microgravity". Presentation to the AE School Advisory Group, 1997
13. Komerath, N.M., Acoustic Shaping, Inc.: Business Plan for Space-Based Manufacturing". Paper 505, Session 1454, Proceedings of the ASEE 2000 National Conference, St. Louis, MO, June 2000.

VII. Biographical Sketches

Sameh Sadarous Wanis is a senior in Aerospace Engineering at Georgia Institute of Technology. He is the initiator and leader of the Acoustic Shaping project. He transferred from U. Florida to Georgia Tech in 1995. He worked as a Co-Op in the Engine Maintenance section of Delta Airlines' Engineering Facililties at Atlanta during his sophomore and junior years, and has been a member of the Experimental Aerodynamics Research Group in AE since his sophomore year. He expects to graduate with the Bachelor of Science in Aerospace Engineering degree in December 1999 and enter graduate school.

Dr. Narayanan Komerath, Professor in AE and director of the John J. Harper wind tunnel, leads the Georgia Tech Experimental Aerodynamics Group (EAG). He has taught over 1600 AEs in 19 courses in the past 15 years. He is a principal researcher in the Rotorcraft Center of Excellence at Georgia Tech since its inception in 1982. He is an Associate Fellow of AIAA. EAG research projects have enjoyed the participation of nearly 100 undergraduates over the past 14 years. EAG is a leader in multidisciplinary team-oriented projects, including the Aerospace Digital Library Project at Georgia Tech: http://www.adl.gatech.edu

Dr. Erian A. Armanios, Professor in AE and director of the NASA Georgia Space Grant Consortium, received his B.S. in 1974 and M.S. in 1979 in Aeronautical Engineering from the Cairo University, and his PhD in Aerospace Engineering from Georgia Institute of Technology in 1985. He has worked with the French National Railways, Cairo University and the Steel Consulting Office in Cairo, before joining Georgia Tech. He conducts research in the field of composite materials, and is a principal investigator at the Georgia Tech Rotorcraft Center of Excellence.