Tailored Force Fields for Space-Based Construction

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Abstract. In Space, minor forces exerted over long periods can produce major results. Force fields of various kinds can be used to build large structures, superseding the human-intensive construction techniques of today. In this paper we consider how several techniques now used in other fields can be generalized and applied to Space-based construction. Radiation pressure exerted by coherent beams on scattering objects is today used in microscale positioning. Standing-wave fields offer important advantages - the radiation force in a standing wave field can be 3 orders of magnitude greater than that of the source. The strong analogy between optical/electromagnetic and acoustic radiation is used to extend a microgravity flight result from acoustic standing wave fields to electromagnetic fields. - walls of complex shape can be formed automatically. The interim architecture to bootstrap an economy which will permit large-scale construction projects is briefly considered.

INTRODUCTION

In Space, minor forces exerted over long periods can achieve major results. This fact offers a way to solve some of the basic problems which hinder human ambitions to develop a Space-based economy with permanent, large-scale habitats. In the 1970s, O'Neill (1977) and Johnson et al (1975) considered the problem of building large habitats in some depth. Three basic points emerged:

1. Large habitats for a distributed economy were ideally situated in orbit, not on or below planetary surfaces.
2. Long-term human residence in Space required artificial gravity, spin rates below 1 rpm, and most of all, radiation shielding which would stop all ionizing radiation.
3. Human labor for construction would be prohibitive in both hazards and cost.

Given these constraints, there was no practical solution. The mass needed for full radiation shielding was immense, and techniques for assembly of the outer shell and shield of any such habitat demanded millions of human work-hours. This is the problem which motivates part of the work presented here.

Various kinds of force fields are used today. Forces exerted by radiated energy on objects in their path, have been proposed for space propulsion (Tsander 1924, Forward 1984 &1985). "Optical tweezers" are used in materials research and microscopy to manipulate micro- or nano-particles. McCormack (2002) has proposed applying laser beam / particle positioning in orbit to form mirrors for space telescopes. Ultrasonic beams are used to hold small objects (mm scale) away from solid surfaces for non-contact processing. NASA uses Electrostatic Levitation (ESL) for non-contact positioning involving small particles of some materials. In this paper we attempt to develop a uniform view of such phenomena, in terms of relations between frequency, wavelength, and particle dimensions.

In past work (Komerath et al. 2001, Ganesh et al 2002) we have shown that quasi-steady magnetic fields can be used to solve the problem of building a massive radiation shield and outer structure for a 1km-radius, 2km-long cylinder at a Lagrangian point of the Earth-Moon system. Such a project draws upon several technologies such as lunar-based solar power plants, in situ resource extraction, electromagnetic launchers and tethers. However, it also provides the means to develop a coherent plan to bootstrap all of these technologies and give each the markets needed for commercial viability. The level of public investment needed for such huge projects may in fact be surprisingly moderate when set in the context of a synergistic plan to build infrastructure beyond Earth. Here our objective is to explore the tailoring of more generalized force fields to generate entire surfaces of complex shape. This again has a number of applications related to a future Space-based economy – and eventually to the automatic formation of very large structures from asteroid material using converted solar energy. We explore acoustic, magnetic and long-wave electromagnetics.

PREVIOUS WORK

It is known that optical radiation exerts pressure on solid objects. Solar radiation pressure is significant enough at the orbit of Earth to be included (Hamilton et al, 1996) as a low-order effect in trajectory calculations for dust in the vicinity of Earth. When solid particle radius is less than 5% of the incident wavelength, the force exerted on a particle by radiation can be modeled using Maxwell's relations, simplified for the Rayleigh regime (Harada 1996). Here the phase differences between radiation falling on different parts of the particle are negligible, simplifying the interference between incident and scattered radiation. In this regime, particles experience a net force in the direction of the incident beam, where there is only one beam, but in the direction of increasing intensity (towards the beam waist) if the beam is focused. Zemanek et al (1998) discuss the trapping force experienced on such particles. This phenomenon is used in optical microscopes to hold illuminated specimens in place. Positioning is improved when the reflected beam from a mirror interferes with the incident beam. Gomez-Medina (2001) discusses radiation pressure on neutral particles in a waveguide. Zemanek et al (1998) have shown that radiation forces can be increased by 3 orders of magnitude, and the "trap stiffness" increased by seven orders of magnitude, when a standing wave pattern is created. Particles move towards nodes or antinodes of the standing wave field depending on their relative refractive index.

Similar phenomena occur in the field of ultrasonics (King 1935, Whymark 1975). Beissner (1986) discussed models for the radiation pressure in ultrasonic fields from the points of view adopted by Langevin and Brillouin, and compared them in the context of measurements of the radiation force on an absorber at oblique incidence. Collas (1989) showed results on acoustic levitation in ground experiments. Yarin et al (1998) calculated acoustic radiation pressure using a boundary element method and predicted shapes of levitated droplets, which showed good agreement with experimental measurements. They showed that displacement of the droplet center relative to the pressure node due to the presence of gravity (or other steady force) was significant and could be computed. Wang and Lee (1998) reviewed the subject of radiation pressure and acoustic levitation, keeping in view the applications to containerless processing in microgravity. In these applications, ultrasonic frequencies were used, with extremely high amplitudes achieved in the resonator. Zhuyou et al (1992) report levels of 183dB inside their ultrasonic levitator used to levitate steel spheres. Eckart (1948) and Wang and Lee (1998) discuss the issues of acoustic streaming inside these chambers, and their influence on the levitated particles. With ultrasonics, the practical size range of levitated particles goes beyond the Rayleigh regime, and the streaming flow around the particles has a profound influence on thermal gradients, spinning motion, vibration and the ability to retain a coherent trapping force.

Wanis et al (1998) from our group recognized that high sound levels are not necessary, and that acoustic manipulation of objects in reduced gravity would work with audible sound frequencies. In experiments aboard the NASA KC-135 flight laboratory, it was shown that positioning worked better when the sound levels were low enough so that the streaming effects were small. Wanis et al (1999 and 2000) extended their flight test results to ground experiments with liquids and powder suspensions. They were the first to show that a multitude of particles inside a resonant chamber would form single-particle-thick walls parallel to the nodal surfaces, and not agglomerate around points of minimum potential.

SCOPE AND OBJECTIVES

In this paper, we start from the observation that the equations describing the generation of radiation forces and trapping stiffness in optics and acoustics are similar. We confirm this similarity through results from flight and ground experiments using audible sound, comparing them with results from optics and ultrasonics in other wavelength and size regimes. Our results on acoustics show that complex surface shapes can be generated by suitably tailoring frequency and resonator geometry. Predictions for cylindrical and rectangular resonators show that various surface shapes of practical interest can be generated. We generalize these observations to explore the use of long-wave electromagnetic fields to move and position construction raw material in microgravity along desired wall shapes, automatically and gradually, using a continuous input of solar-derived energy. A comparison is developed where particles of the same material are used with optical, acoustic and microwave fields, exploring the power requirements in different wavelength regimes to achieve the acceleration level needed to overcome noise. The comparison is confined to the case of transparent materials in standing wave fields.

GENERALIZED RELATIONS

From Maxwell's Equations, the undamped electromagnetic wave equation in a non-dissipative medium is:

$$\nabla^2 E - \varepsilon\mu \frac{\partial^2 E}{\partial t^2} = 0 \qquad (1)$$

A critical parameter for determining the interaction of radiation with solid particles is the refractive index. In the Rayleigh regime where target particle radius is much smaller than the wavelength ($a < 0.05\lambda$) the particle experiences a uniform instantaneous field due to the electromagnetic wave. Only the electric field need be considered, which makes the problem equivalent to that of an isotropic, homogeneous, dielectric sphere in a uniform field. A spherical target in this size range acts as an oscillating electric dipole. For an incident wave of unit intensity, and transparent particles (refractive index mostly real) the scattered intensity (Zemanek *et al*, 1998) is:

$$I = \frac{16\pi^4 a^6}{r^2\lambda^4} \left| \frac{m^2-1}{m^2+2} \right|^2 \sin^2 \psi \qquad (2)$$

The main feature of Rayleigh scattering in the above is the dependence of the scattered intensity upon the *inverse fourth power of the wavelength*. Total scattered energy can be obtained by integration over the sphere surface. When a wave is reflected off a mirror and a standing wave pattern is formed, there are sharp intensity gradients in the beam. Under these conditions, the two main contributions to the electromagnetic forces acting on the particle in a standing wave field are the Gradient force and the Scattering force. Following Zemanek *et al* (1998):

$$F_{grad}(z,r) = \frac{2\pi n_2 a^3}{c} \left(\frac{m^2-1}{m^2+2} \right) \nabla I(z,r) \quad ;$$

$$F_{scat}(z,r) = \frac{16}{3} \frac{n_2}{c} k^4 a^6 \left(\frac{m^2-1}{m^2+2} \right)^2 \frac{P}{w^2} e^{-2r^2/w^2} \left(r^2 - 1 \right) \quad . \qquad (3)$$

Zemanek *et al* (1998) show that a standing wave field produces a gradient force 3 orders of magnitude stronger, and a trapping stiffness at the stable points that is 7 orders of magnitude higher, than for cases where a single beam is used. The force expressions in the electromagnetic field are similar in form to those in the acoustic field, for the moderate-intensity, Rayleigh regime of acoustics where the acoustic streaming and the generation of harmonics by nonlinearity are absent. The electromagnetic fields do not offer mechanisms for the generation of such nonlinearities in their simple form, though such effects cannot be ruled out when interaction with large numbers of particles is considered in detail. Parameters may be compared roughly as shown in Table 1. While small, the acoustic field numbers in Table 1 are seen to be adequate (Wanis et al 1999) to rapidly form walls with various types of particles, even in the presence of g-jitter of the order of $1 m/s^2$.

TABLE 1. Important Parameters and Orders of Magnitude: Comparison of Optics and Acoustic Force Fields.

Parameter	**Optics**	**Acoustics**
Stress term	Maxwell's stress tensor	Radiation stress tensor
Rayleigh regime size	Nanometers	Millimeters to centimeters
Material parameter	Refractive Index	Density ratio of particle to medium
Intensity	Optical intensity	Sound pressure fluctuation intensity
Force order of magnitude	Zemanek (1998): 514.5 nm laser; beam waist of 8 λ; 5nm glass sphere in water, m= 1.51; Force = $2.5 * 10^{-22}$ N.	Wanis(1999): 156 dB at 800 Hz (1 0 0) mode at 2mm radius rigid particles. Force = $3.3 * 10^{-6}$ N

In Figures 1-3, this comparison is extended to a standing microwave field to get a different range of wavelength and particle size. In this first consideration of the generalized problem, we used the following logic to enable a direct comparison of different types of waves and particles, drawing upon each application area. Optical tweezers usually use visible wavelengths and the theoretical expressions are simpler for transparent particles (glass, which is mostly silicon dioxide). Microwaves transmit through silicon dioxide, and acoustic shaping works on most materials. This enables us to choose material of the same density (roughly 2000 kg/m^3), and assume the refractive index of glass relative to vacuum for both the optical and microwave cases. In Figures 1 – 3, the force per unit incident radiation intensity is divided by the mass of a particle to obtain the acceleration per unit intensity. In the case of gradient forces, the gradient is approximated by dividing the intensity by a quarter-wavelength. The abcissa is the particle radius. For each particle radius, it is assumed that the wavelength used is 20 times the particle radius to stay within the Rayleigh regime definition and remove some of the wavelength dependence. The acceleration in each case depends inversely on particle radius. This poses a drawback in dealing with raw material until powerful long-wave resonators can be developed, or we learn to generate adequate coherent forces in the Mie scattering regime.

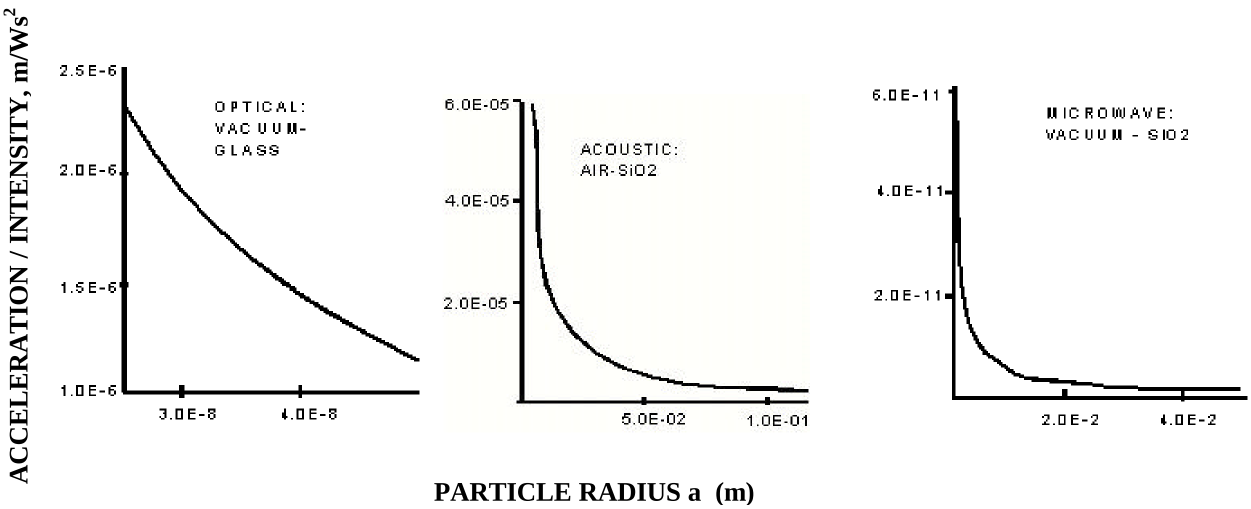

FIGURE 1. Ranges of particle acceleration per unit radiation standing wave field intensity, as functions of particle size, for optical, microwave and acoustic fields. In each case, the radiation wavelength is set to 20 times the particle radius.

The above results indicate that high microwave intensity would be required to move particles. It is a good rule of thumb that intensities achievable inside resonators can reach 3 orders of magnitude higher than source beam intensity. Our experiments on acoustic shaping (below) show that $40kW/m^2$ corresponding to the 156dB resonant field shown in Wanis (1999) is adequate for forming walls from ceramic materials in acoustic resonators. Microwave beam intensities up to $8MW/m^2$ have been demonstrated in ground-based laboratory experiments (Beauvais, 1997) – thus we may expect to achieve microwave resonator intensity in space experiments of $8GW/m^2$. It thus appears reasonable that microwave-induced electromagnetic shaping using raw materials such as silicon dioxide (primary component of lunar regolith) is feasible in prototype experiments.

RESULTS ON ACOUSTIC SHAPING

In the preceding sections we showed that significant forces could be generated in unsteady fields, especially standing wave fields, due to interaction between the field and solid (or liquid particles). Comparison of optical, microwave and acoustic forces shows that significant accelerations, much higher than the disturbances from "g-jitter" in orbit, can be achieved using all three kinds of waves. In the following section, we show flight validation of the idea of using such forces in a resonant field, to form prescribed shapes of walls. Acoustic shaping in reduced-gravity experiments is used, since an opportunity provided by NASA on their Reduced-Gravity Flight Laboratory made this feasible.

Wanis et al used a rectangular plexiglass box with speakers mounted on two sides across a corner. Only the speaker set in the end face was used in the results shown here. With solid particles placed inside the box, the speaker driven at a natural frequency of the box, and the setup flown in reduced gravity, the particles migrate rapidly and stand along the nodal planes of the box, as shown in Figure 2. This is a crucial demonstration: in the ultrasonics and optics experiments, the primary interest was in holding one or more particles close to a pre-selected point of minimum potential. Here it is seen that when a multitude of particles are placed in a resonant potential field, they migrate, not to the single point of least potential, but to fill entire surfaces. These are thus self-forming walls – videotapes of the flight tests show that the particles "jostle" each other and fill up vacant spaces in the walls.

Various other results have been obtained on such wall formation – these are reported in Wanis et al (1998), Wanis et al (1999) and (2000). As shown by Wanis et al (1999), the mode shapes even for a rectangular container can be quite complex, and the measured locations of the walls are parallel to or coincident with the nodal surfaces. In Figure 3, various possibilities are explored, for combining harmonics to obtain interesting solid object shapes. The technique has also been shown to work with liquids in reduced (but not zero) gravity, as well as with powders suspended on liquids. The particle vibration and spin problems observed in the Mie regime for optic and ultrasonic positioning experiments, is not observed, and indeed are not expected.

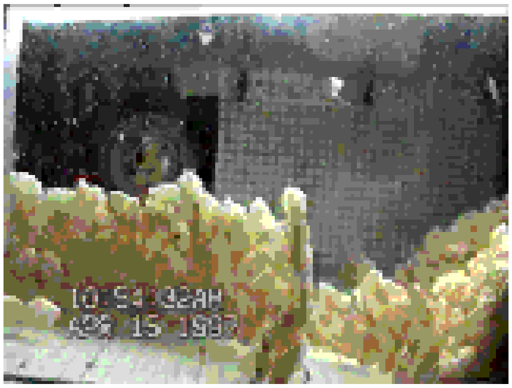

FIGURE 2. Single-particle thick walls of irregular ellipsoidal grains, forming parallel to the nodal surfaces in reduced-gravity flight experiments.

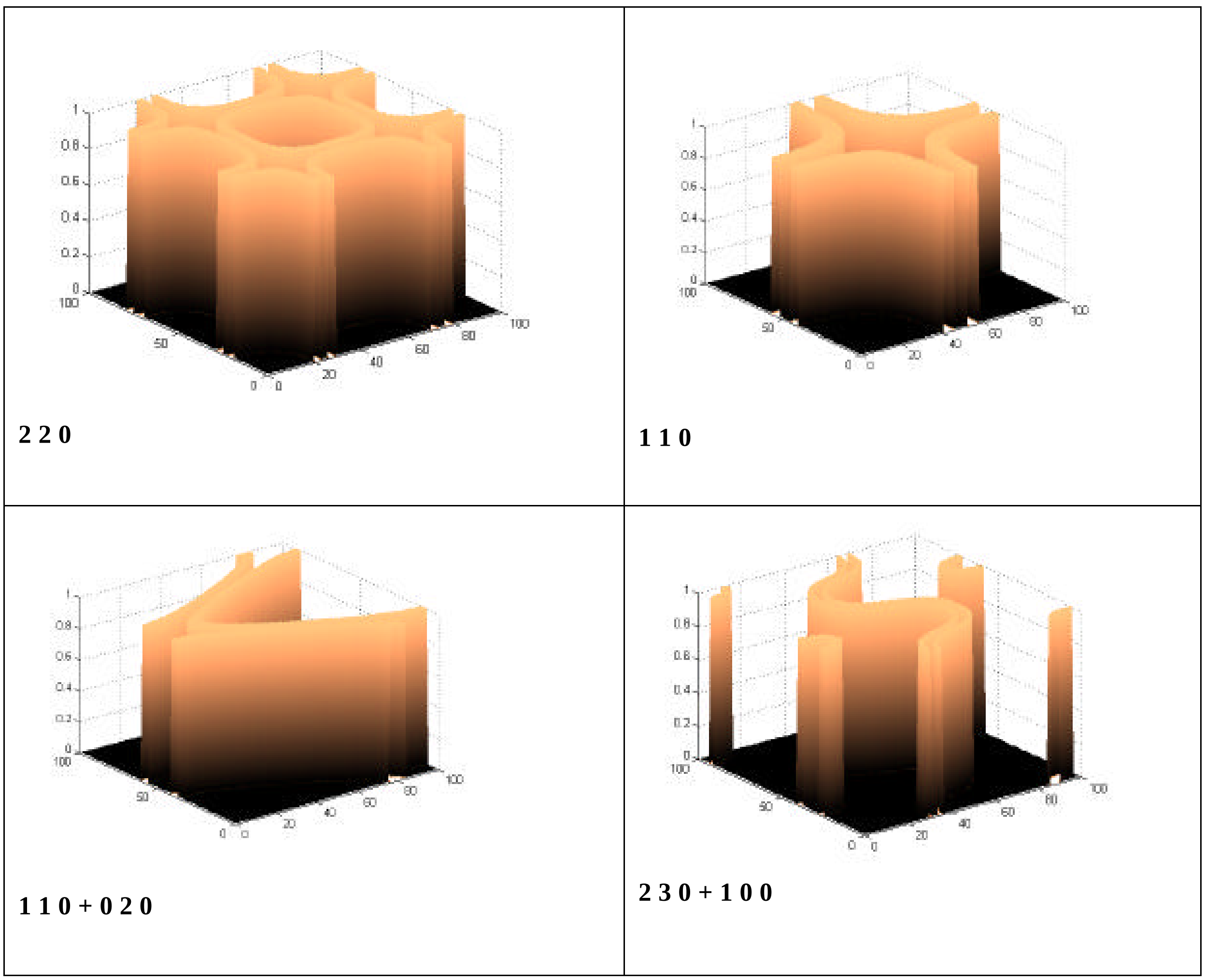

FIGURE 3. Simulation results on useful wall shapes combining low-order acoustic modes in a rectangular chamber.

ELECTROMAGNETIC CONSTRUCTION

While the formation of parts by acoustic shaping is feasible today, acoustic shaping requires containers with gas atmospheres. The formation of walls and useful shapes from microwave and other electromagnetic radiation can be performed in vacuum, but require substantial power sources, and will become realistic when there is a movement towards the construction of large space-based power sources such as solar power satellites (Shaposhnikov 2002). For any large-scale construction in Space, massive resources from extraterrestrial locations (Moon or asteroids) are essential. Large-scale extraction of extraterrestrial resources requires an economic framework with long-term payoffs. In Komerath et al (2001) and Ganesh et al (2002), we discuss an architecture for building the first massive human habitat at the Earth-Moon L-2 or L-5 regions, as part of a coherent plan for a Space-based economy. The project is conceived as a synergy between concepts for lunar-based solar power plants, lunar robotic mining and metal processing, robotic fabrication plants, and a set of 10 electromagnetic launchers as a lunar equatorial space launch systems. Railcar-sized rectangular containers filled with 2 m thickness of lunar regolith (dominantly SiO2) are launched off the lunar surface. They are captured in space by "shepherd" space tugs which guide them to the axis of the cylinder, and positioned using an electromagnet grid onto the outer cable grid of the cylinder, before being robotically fixed to each other. A quasi-steady magnetic positioning and assembly technique is used in this process.

CONCLUSION

In this paper we have presented the idea of tailoring unsteady potential fields to form solid particles of arbitrary shapes into walls of prescribed geometry. We have considered applications and theoretical results from optics and acoustics to show that the force generation mechanisms bear similarity. Choosing a material with a wide range of forms, but generally uniform density (silicon dioxide as glass and regolith) we have performed a direct comparison of the particle accelerations achievable using optical, microwave and acoustic standing wave fields. Experiments using acoustic shaping confirm that particles of arbitrary shape migrate rapidly to nodal surfaces whose shapes correspond to simple predictions. Generalizing using the similarities between different wave fields, we conclude that electromagnetic shaping could become a viable option to consider for automatically forming useful objects in Space, when high-power, long-wave resonators are developed.

NOMENCLATURE

(All dimensional quantities are in SI units)

a: particle radius
E: electric Field Intensity
I: intensity
k: wave number
m: ratio of refractive indices: particle n_1 to medium n_2
P: beam power
r: radial distance
w: beam width
z: axial distance

ε: permittivity
μ: magnetic permeability
λ : wavelength
ψ: phase
σ: specific conductance
ρ: absolute value of Fresnel reflection coefficient of surface; used in forming standing wave.

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