Sail Deployment By Microwave Beam—Experiments And Simulations

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Abstract. Unfurling and deployment of large-area, membrane structures in space is essential for many NASA purposes, such as large ultralight antennas and mirrors, occulters, collectors for SPS, and sailcraft for deep space exploration. Deployment is a complicated electromechanical problem, exacerbated by the difficulty and expense of realistic lab or space experiments. The requirement is to open and control very light but very large structures with a minimum of mechanical contact ('hands-off'), deployed from a minimum stowed volume (maximum packing fraction), while providing for control after deployment. We report here on a project that addresses deployment of carbon and other light materials by use of spin, charge and elastic forces. Last year we demonstrated microwave-driven spin of several types of sail by using polarized microwaves at JPL. In the first phase, we conducted experiments to study microwave beam-driven spin deployment, simulating this deployment and its extension to large structures in space. We will determine how efficiently spin forces couple to sail materials, what geometric shapes and material factors influence this electrodynamic efficiency, and develop analytical scaling rules for spin unfurling. This work is conducted under the Gossamer Program.

INTRODUCTION

Unfurling and deployment of large-area, membrane-type structures in space is useful for many NASA purposes, such as large ultralight mirror deployment, collectors for SPS, and sailcraft for Deep Space exploration. Deployment is a complicated electromechanical problem, exacerbated by the difficulty and expense of realistic lab or space experiments. Requirements are, for example, to

1) deploy and control very light but very large structures with a minimum of mechanical contact ('hands-off'),

2) deploy with a mininum stowed volume (max packing fraction),

3) provide for control after deployment.

The lightness and elasticity of the new ultralight carbon fiber sails allows formation and management of space structures (e. g., sailcraft, collectors, and mirrors) with small forces, using no external mechanical contact. A major feature of such electromagnetic handling is that deployment of large sails can be done entirely hands-off. The new carbon sails open up new methods of deployment, which we plan to demonstrate and test experimentally. The methods are:

- Spin deployment: A large, folded sail can be opened with a purely electromagnetic torque exerted by a microwave beam. The directing microwave beam can carry angular momentum, if it is circularly polarized. The force spinning up a sail can be comparable to the electromagnetic (pressure) force on the receiving area. Microwave-driven spin has just been demonstrated in laboratory experiments by this team.

- Elastic deployment: Opening of smaller sails using the rolling-up forces. Their high elasticity unrolls a page-sized sheet in ~1 sec.

- Electrostatic deployment: Uses the repulsive force by placing a charge on a folded sail. Our present data shows that ultra-thin carbon microtruss can hold charge indefinitely.

We are conducting these deployment studies as a continuation of research on sails for propulsion (Benford, 2001, Schamiloglu 2001 and 2002)

DEPLOYMENT MECHANISMS

This project that addresses deployment of carbon and other light materials by use of spin, charge and elastic forces, which we now expand upon:

Spin

A description of spin physics appears in reference 1. We have recently demonstrated microwave-driven spin of several types of sail by using polarized microwaves at JPL. To give substantial spin we suspended the sails using carbon fiber threads of ~7 micron diameter. Their small diameter gives them little torsional rigidity. With this setup we observed 10 Watts spin a light aluminum sail of 3 cm diameter. Similar techniques are being used in deployment experiments.

Our recent JPL experiments show that spinning by reflection requires special sail geometries, which affects the coupling efficiency. Since $\lambda/D\sim1$ in these experiments, a simple model for individual photon reflection from surfaces cannot account for the wave sensing the entire geometry. To an incoming wave a cone will appear like a flat plane, which reverses polarization in the reflecting wave, so no net angular momentum conveys to the cone. In the $\lambda/D\sim1$ regime it is difficult to spin a conductor unless the conducting path for the circularly polarized electric field is interrupted by cuts.

This physical reasoning agrees with the results of our experiments. An aluminum cone did not spin unless two radial slots are cut in it, which shorts out the azimuthal current, destroying symmetry. Then the sail spins readily. Similarly, a flat aluminum plane does not spin. However, given the relative ease of using Al sails, we will first concentrate upon them for early deployment studies.

An absorbing sail will always spin, however. Sail spin experiments using absorbing ($\alpha\sim0.1$) Carbon-Carbon sails have been done at JPL. We are continuing spin physics work, but with emphasis on deployment. Our concept for a spin deployment experiment is shown in Figure 1.

Elasticity

We know that foot-sized carbon-carbon sails can extend themselves if rolled up. Their random fiber structure gives them elasticity greater than conventional carbon forms. The maximum size of a structure which elastic forces can open is set in zero gravity by the mass and moment arm of the sail, favoring materials without many rigid elements. Essentially the deployment energy is provided by the elastic work done. Simple estimates suggest that sails of ~1 meter can be opened this way. This would allow hybrid depolyment methods, where initial elastic opening is followed by another method. For example, elastic unfurling would serve to assist electrodynamic spin, or charge-induced forces, which open the sail further.

Electrostatic (Charge) Forces

A small charge on a folded or rolled sail can open it through the mutual repulsion of the charges as they spread over the opening sail. The deployment energy $W \sim Q^2/4\pi\varepsilon D$ with Q the charge and D the sail size. Three strategies to consider are:

- Q added at the time of folding. When external forces release, this forces open the sail to a minimum-charge-energy shape.
- Q induced by an attached wire. A small battery then delivers the charge, driving the sail open and allowing control of the process.
- Q induced by an outside electromagnetic wave. This relies upon an observed phenomenon: an applied electric wave can thermionically evaporate electrons from the tips of small carbon fibers, leaving behind a net positive charge (see below). This effect depends strongly upon the power of the wave and the fiber size. The electromagnetic wave can be transmitted from nearby and adjusted to shape the sail—for example, inducing an extra charge upon a portion of the sail which has gotten stuck. If the wave is polarized, at the same time it can convey angular momentum to the sail (see below), spinning it up.

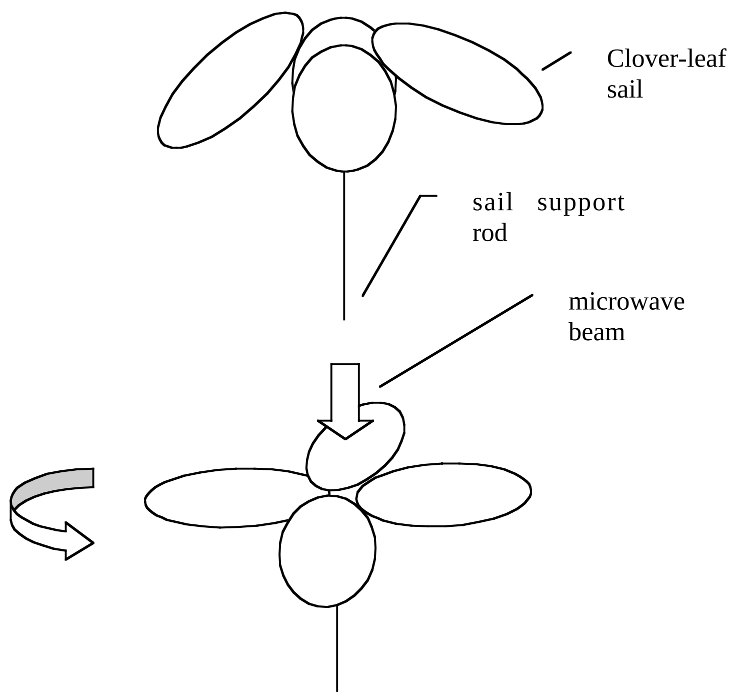

FIGURE 1. Schematic Of Experiment Demonstrating Spin Deployment: Opening Of Cloverleaf Sail By Electrodynamic Spin-Up. Above, the sail droops before beam it turned on. Below, with the beam on, the sail spins, deploys: The clover-leaves open upward against gravity, supported by centrifugal acceleration.

DEPLOYMENT SIMULATIONS

We are using simulations to find the radial size limit for these deployment methods. For large structures, dynamic computer models of the structure's unfurling and operation can aid concept and mission planning. Mature, robust computer codes including all relevant physics/mechanics are available, albeit specialized to a very narrow technical market. They use explicit, time-domain finite element solvers tailored for nonlinear behavior (geometrical and material) to capture dynamic, large-deformation phenomena. An example is codes used to simulate folded automobile airbag deployment.

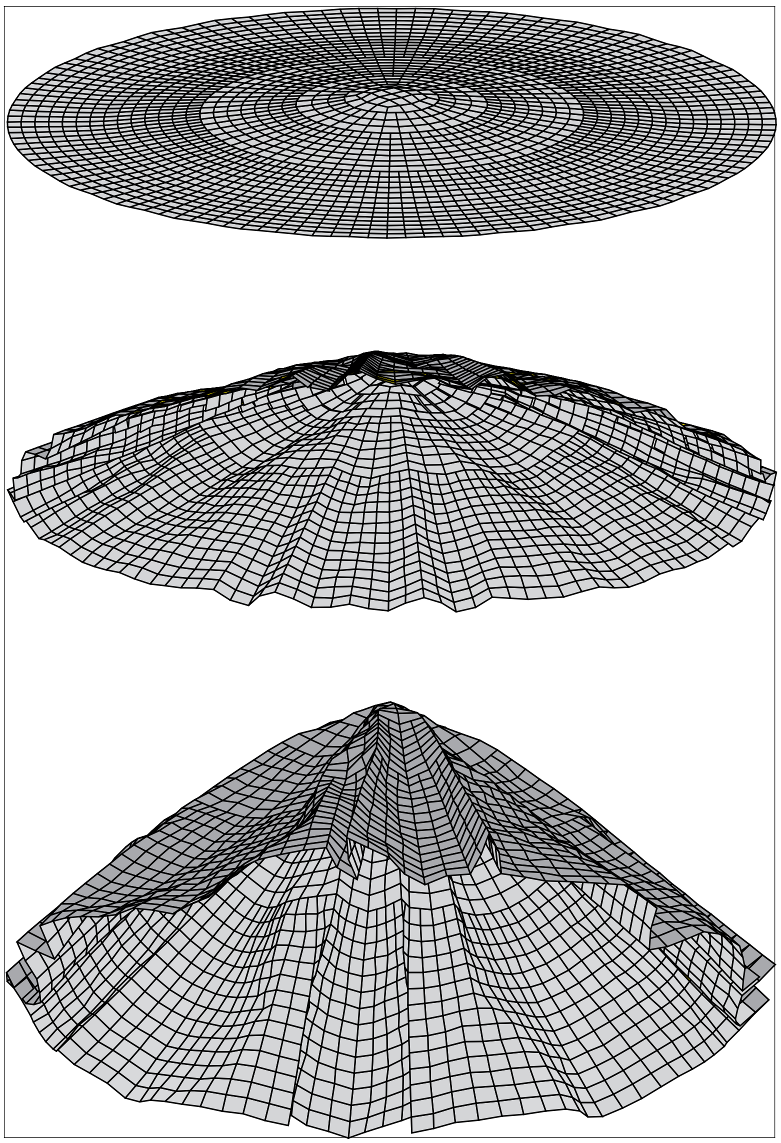

FIGURE 2. Deployment Of A 1 Meter Sail By Centrifugal Force. We are carrying out deployment demonstrations and simulations by several different physical mechanisms. Sail has stiffness and mass density of the carbon micro-truss sail material, and microwave pressure supports it against gravity. Simulation snapshots show large-deformation and folding is corrected by spins of 0.5, 1.0, and 2.0 revolutions/sec (bottom to top). Spin is necessary for rigidity of sails without structural stiffening.

We have conducted simulations of deployment and unfurling from a folded configuration (shown in Figure 1). We then compared with experimental results. Forcing functions include internal stresses, microwave polarization-induced spin-up, and/or microwave reflection/absorption. The experiments will open a variety of sail "skirts". . These experiments employ a ~ 10 kW microwave 10.3 GHz source in high vacuum. The sail can be carbon-carbon fiber, aluminum, or a combination.

Figure 2 shows a simulation of a large 1-m sail as it opens due to spin. Our exploratory calculations of sail deployment include both dynamic deployment with and without spin, collapse due to gravity, and spin redeployment. [Spin is required to maintain a flattened, stable sail without stiffeners.] Simulations can also include sail mechanical response to radial variation in thrust due to microwave beam power.

CONCLUSIONS

We are conducting laboratory exploration/demonstrations of deployment of ultralight (sail) materials using spin, charge and elastic forces. We are also simulating deployment of ultralight materials. Our first experiments test the general principle of electrodynamic deployment, allowing a near-term very large sail deployment demo and scaling to space missions within ~10 years.

ACKNOWLEDGMENTS

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