DESIGN, FABRICATION, AND TESTING OF A GRAPHITE-EPOXY COMPOSITE GRAVITY-GRADIENT BOOM FOR A SMALL SATELLITE

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Abstract

Passive stabilization methods for satellites have undergone extensive research and development. Recently the number of small satellites (satellites less than 100 kg.) has increased dramatically. This has lead to increased use of passive stabilization methods, such as gravity-gradient. The core of a gravity-gradient stabilization system is a deployable boom with a damping mechanism. Traditionally, this boom is constructed from metal alloys. Uneven heating and cooling occurs when these alloys are exposed to varying solar radiation conditions. This can induce thermal vibrations which can lead to undesired satellite attitude inversions. Graphite-epoxy composites can be fabricated to minimize thermal expansion. This will be beneficial when applied to gravity-gradient booms. The goal of this project is to demonstrate the use of graphite-epoxy composites in gravity-gradient booms. This project encompasses: the use of a satellite attitude simulation program for boom sizing and determination of gravity-gradient boom loading, development of joint-locking mechanisms for boom deployment, and selection and testing of appropriate fabrication methods.

Gravity-Gradient Stability

The Earth's gravitational field provides a ready source of stability for satellites in low Earth orbit. The inverse square nature of the Earth's gravitational field causes a torque to act on a spacecraft in orbit. This torque causes the spacecraft's principal axis of minimum moment of inertia to align itself with the local vertical.[1] The magnitude of the torque is a function of the distance from the center of the earth (orbital radius) and the ratios of the mass moments of inertia. A cartesian coordinate system is introduced with the origin at the spacecraft center of mass, with the x-axis along the orbital velocity vector, y-axis perpendicular to the orbital plane, and the z-axis nadir pointing and completing a right-handed system.

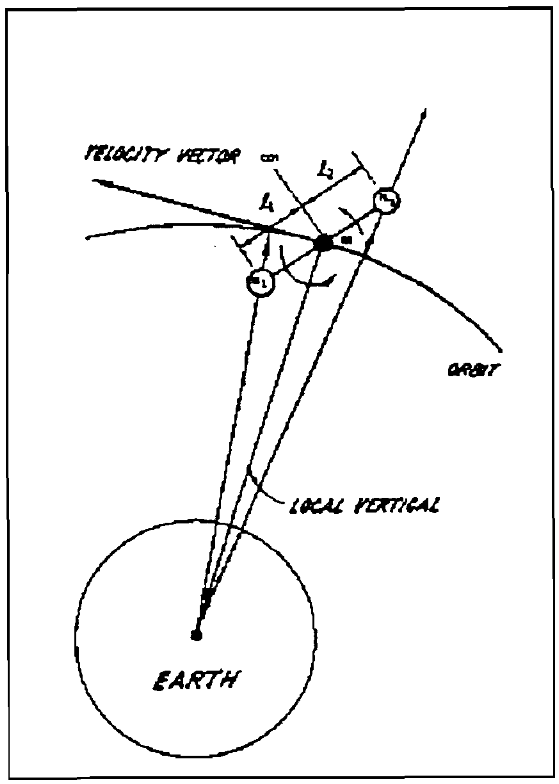

Figure 1. Spacecraft Axis System[2]

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Figure 1 shows a model satellite in Earth orbit for reference. The spacecraft's stability in a gravity-field can be measured by the introduction of three stability criteria[3]:

$$\Theta_x = (I_y - I_z) / I_x \qquad (1a)$$

$$\Theta_y = (I_x - I_z) / I_y \qquad (1b)$$

$$\Theta_z = (I_x - I_y) / I_z \qquad (1c)$$

These criteria represent the stability of a satellite as the ratios of mass moments vary. This is shown graphically in Figure 2. Most spacecraft are symmetric about the z-axis so that $I_x=I_y$. When $I_x=I_y$, the region of stability lies along the Θ_x axis, and the only criterion of interest becomes Θ_x. With an axisymmetric spacecraft, equation 1a above reduces to:

$$\Theta_x = 1 - (I_z / I_x) \qquad (2)$$

The determining factor for stability then becomes the ratio of I_z to I_x. Note that as I_x increases, Θ_x approaches its limiting value of unity. Equation 2 suggests that shapes with an I_z/I_x ratio near zero are the most stable. This corresponds geometrically to long, slender objects.

Spacecraft design considerations such as packing arrangements, thermal control, and available launch envelopes do not always allow for the use of long, slender bodies. However, the mass moments of inertia of spacecraft may be modified once in orbit to achieve the desired stability. While many possibilities exist to achieve a favorable mass moment ratio, (I_z/I_x) one of the most common methods is the deployment of a long boom with a tip mass; more often known as a gravity-gradient boom.

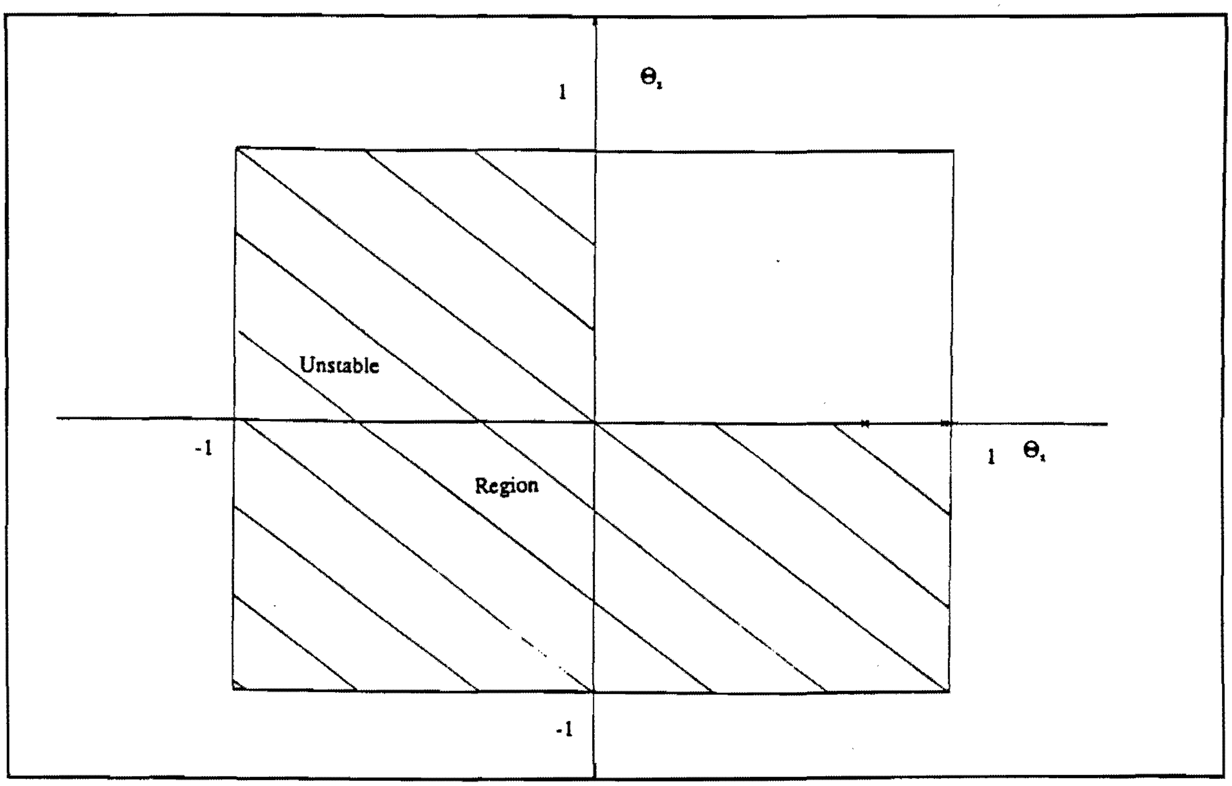

Figure 2. Stability Field

Gravity-Gradient Booms

Considerable research effort has been directed toward development and testing of gravity-gradient booms. These efforts include the development of several types of booms. A bi-metallic boom was most frequently used. This consists of two thin strips of metallic alloy approximately 0.005 centimeters. (0.002 in.) thick. Beryllium-aluminum and beryllium-copper were commonly used in this application. These two strips were carried into orbit in coils, much as common tape measures are stored. A motorized unit would unwind the two tapes. The tapes would then buckle together, inter-locking to form a closed section. This type of boom continues to be used today. Figure 3 shows some representative of this type of boom.

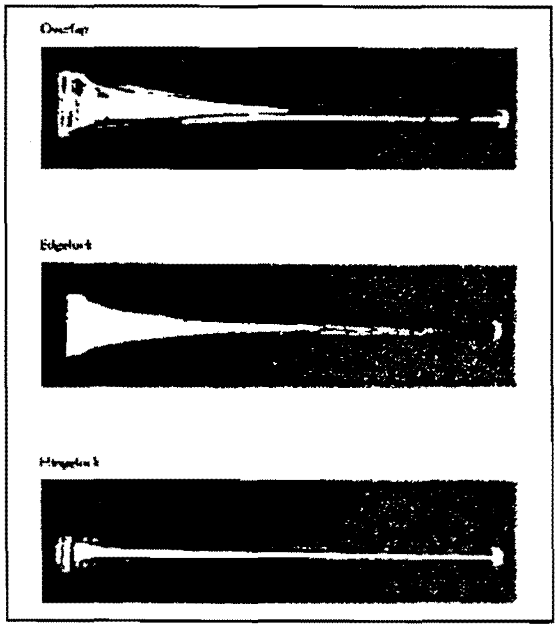

Figure 3. Tape boom examples[2]

Several difficulties arose with this design. Despite the closed section, the deployed boom is weak in torsion. The design has also been observed to experience thermal flutter. Thermal flutter is the bending of the boom out of the desired plane due to uneven heating. This bending changes the spacecraft's inertia properties and causes undesirable attitude behavior. The behavior has been severe enough to cause satellite attitude inversions as documented in the HILAT and Polar BEAR[4, 5] spacecraft.

As more small satellites are constructed, complexity becomes a planning consideration. The support system for the tape-design booms includes a motorized deployment system. This system introduces mechanical uncertainty and power requirements into the design of a spacecraft. Simplification of this system would reduce spacecraft complexity and remove potential sources of failure.

Composite Material Application

The two most significant drawbacks of the currently available gravity-gradient booms are their complexity and undesirable thermal behavior. Only limited success has been achieved with the use of coatings to control the thermal properties of metal alloys. The mechanisms for deployment of metal alloy booms also remain complex. The application of composite material technology can be used to address these two considerations.

Composite materials can be fabricated with favorable thermal expansion characteristics. By varying ply orientations and sequences, it is possible to create a material with a near zero coefficient of thermal expansion. Composite materials designed with low thermal expansion coefficients could be applied to current design configurations. This should reduce the effects of thermal flutter and its associated satellite attitude disturbances.

The mechanical properties of composite materials also allow for several possible design changes. The favorable strength to weight ratio of composite materials allows for smaller closed section designs. This facilitates the use of a telescoping design which can be carried internally as a closed section. Telescoping closed section designs do not require a drive motor for deployment. A closed section may be deployed by a spring system or by use of a gas charge to pressurize the internal volume of the boom. Either of these deployment systems would require less volume and would be less complex than a motorized unit.

Boom Section Development

Work began to study various boom section configurations to determine their feasibility. At this point, no consideration was given to final boom size (length, diameter, tip mass, etc.) or loading conditions. Rather, efforts were focused on the cross-sectional properties and methods of deployment.

Figure 4 shows the first open-section concept. This design would consist of two "C" sections with flanges attached. To store this structure, the smaller radius "C" section would have to buckle into the larger "C" section.

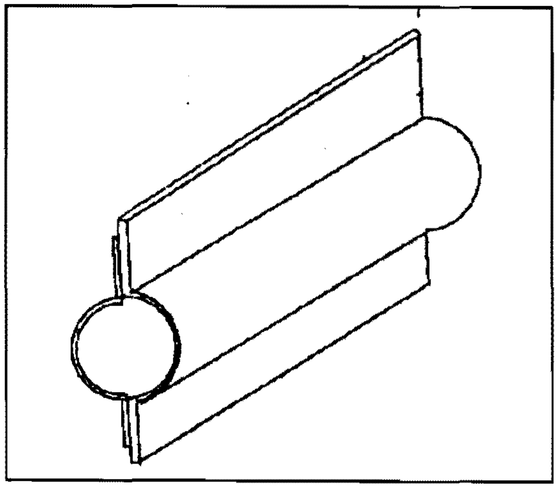

Figure 4. Open-Section Concept 1

Two test specimens of this design were fabricated. The first test specimen consisted of three plys of uniaxial graphite-epoxy composite [0°,90°,0°]. The specimen was oven-cured under vacuum. Two "C" sections were fabricated in succession, with the first, smaller section serving as a mold for the second, larger section. These two portions were then epoxied together to form a closed section. This specimen was evaluated qualitatively to determine its buckling ability. It was found that the smaller section would not buckle without loss of matrix integrity.

The second specimen consisted of two plys of [0,90] woven graphite-epoxy composite. This specimen was constructed using the same method as the first and was also qualitatively evaluated. It was found that the woven material was still too "stiff" to buckle without significant cracks developing in the composite matrix.

Figure 5 shows the second open-section concept. This design would consist of concentric, interlocking "C" sections. The inner, smaller radius section, would slide in rails provided by the outer sections. This design would provide for a telescoping boom.

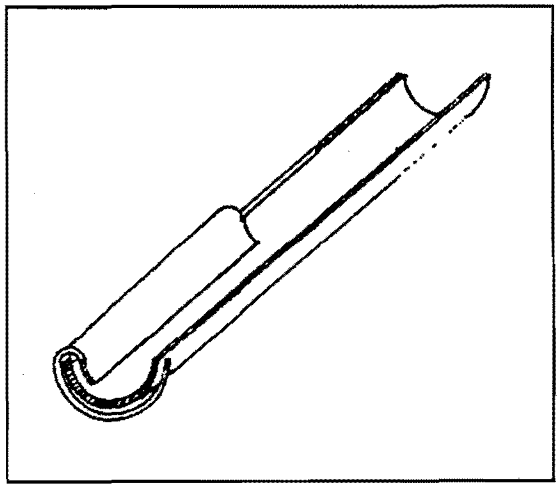

Figure 5. Open-Section Concept 2

Two test specimens of this design were fabricated. The first, or inner section, was fabricated as a "C" section and cured in an oven. The second, or outer section, which provides the slide rails, was then formed over the inner section and cured. After the second cure, it was discovered that the two sections had fused. The fabrication process used did not adequately separate the two sections to prevent epoxy from joining the two sections during the second cure. It was not possible to evaluate this specimen. The second specimen was constructed in the same manner, but with added release material to prevent the fusing of the inner and outer "C" sections. This specimen also used a third outer section. This specimen was again qualitatively evaluated. It proved difficult to fabricate a section with uniform guide rails. This created points along the structure that would bind during deployment or retraction. This difficulty arises out of the fabrication technique and the mandrel that was used. It is possible that with a different mandrel this problem could be corrected. In addition to deployment and retraction problems, this section proved very weak in torsion because of the open-section design. The open-section also exhibits non-uniform bending stiffness, as the test specimen was found to bend very easily in the open direction.

Figure 6 shows the closed-section concept. This design consists of concentric circular sections. This concept would be used much like a telescoping radio antenna with the concentric sections being slid along one another.

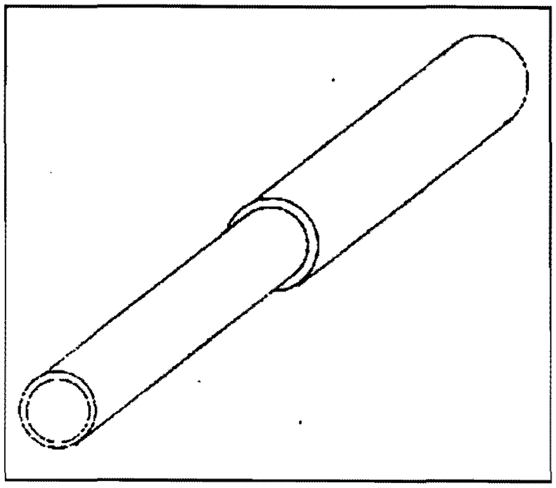

Figure 6. Closed-Section Concept

Deployment/Retraction Methods

Deployment schemes were considered in the development of the three concepts outlined above. The double "C" section (Figure 4) was considered to be deployable and retractable by buckling of the smaller radius "C" section into the larger section, and then "rolling" these two sections on a spool (much like a retractable tape measure). The interlocking "C" section (Figure 5) would be deployed and retracted by telescoping, as would the closed-section.

Several mechanisms were considered to perform these tasks. A servomechanism would be required to deploy and retract the double "C" section by rotating a spool. This would add weight and complexity to the system. A boom of this type would be locked into place by the un-buckling of the smaller section.

The interlocking "C" section could be deployed by a spring. Retraction of this design would be more difficult. One possibility was to attach a cord to the outer section and then reel this cord in to retract the boom. It is still uncertain what type of locking mechanism could be employed to lock the boom in a deployed configuration.

The closed-section could be deployed by a gas charge. This was the simplest mechanism considered. The use of a cord and reel system could provide retraction capability. It may also be possible to design the magnetic portion of the satellite control system to avoid the need to retract the boom once it is deployed.

Boom Section Selection

The closed-section design was selected for further development. This section was chosen for its torsional properties and its uniform bending stiffness. The simplicity of the deployment mechanism was also a consideration. The current assumption is that the magnetic portion of the satellite attitude control system will be able to invert the satellite with the boom deployed, so the boom will only be deployed once.

Figure 7 and Figure 8 show the details of the joint design. Figure 7 is a cut-away of the outer wall of a section. Figure 8 is a view of an inner section, with the outer section not shown. This design provides for a forward stop collar located on the inner wall of the outer boom section, and a series of forward segmented stops located on the outer wall of the inner boom section. A segmented stop collar is also located on the inner wall of the outer section. A rear stop collar is also located on the inner section. When pressurized, the boom extends until the forward stop collar on the outer section comes into contact with the segmented collar on the inner section. The segments on the inner section slide through the gaps in the collar on the outer section, and are then rotated to lock the boom in its deployed state. The joint design also provides for the placement of three gaskets: one each at the base of the inner section, the top and base of the rear stop collar to provide a gas seal for the pressurized deployment of the boom.

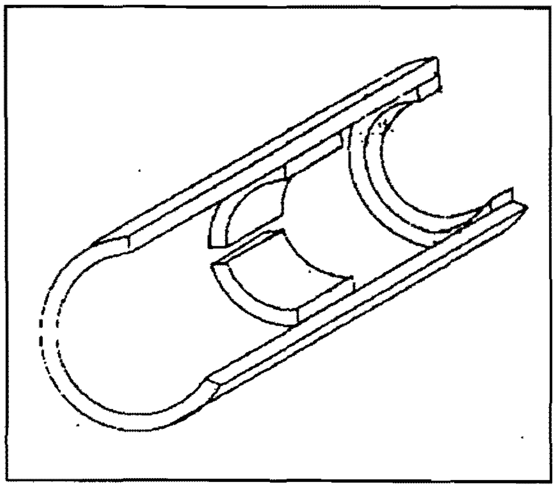

Figure 7. Joint Detail A

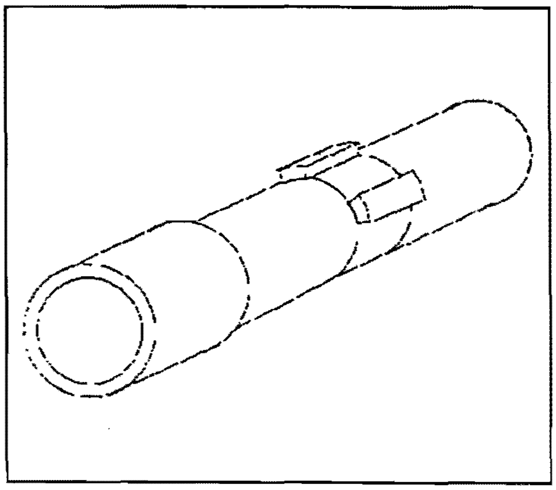

Figure 8. Joint Detail B

Boom Sizing

The operational task of a gravity-gradient boom is to modify the inertia properties of a spacecraft to increase its stability. The degree of stability increase desired is the driving factor in sizing the boom's length and tip mass to a particular satellite. Iowa State University is currently undertaking an effort to design, construct and launch a small satellite, ISAT-1 (Iowa Satellite One). The preliminary design of this

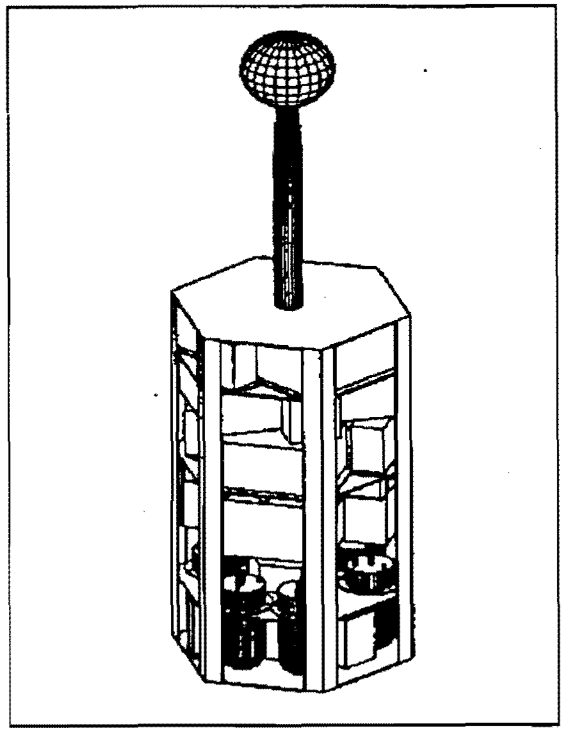

Figure 9. ISAT geometry

satellite was used to size the boom length and mass for this project. The current design configuration of ISAT is shown in Figure 9.

Current efforts of the Iowa Satellite Project provided much of the needed information about the satellite attitude dynamics. Mainly, the attitude determination and control group provided the mass moment inertias of the spacecraft body. These inertias assumed uniform mass distribution within the satellite. A design sizing code with boom length and tip mass as control variables was written to determine an optimum length and tip mass for the satellite. The code allows the user to select the desired stability in terms of the stability criterion Θ_x. The user also selects the desired range of boom lengths and tip masses. The code then iterates through these two variables, calculating the new mass moment of inertia I_x, and uses the new inertia to calculate the value of Θ_x. The calculated value of Θ_x is subtracted from the target value, and the absolute value of the difference is written to a data file along with the boom length and mass. This information can then be plotted on a contour plot.

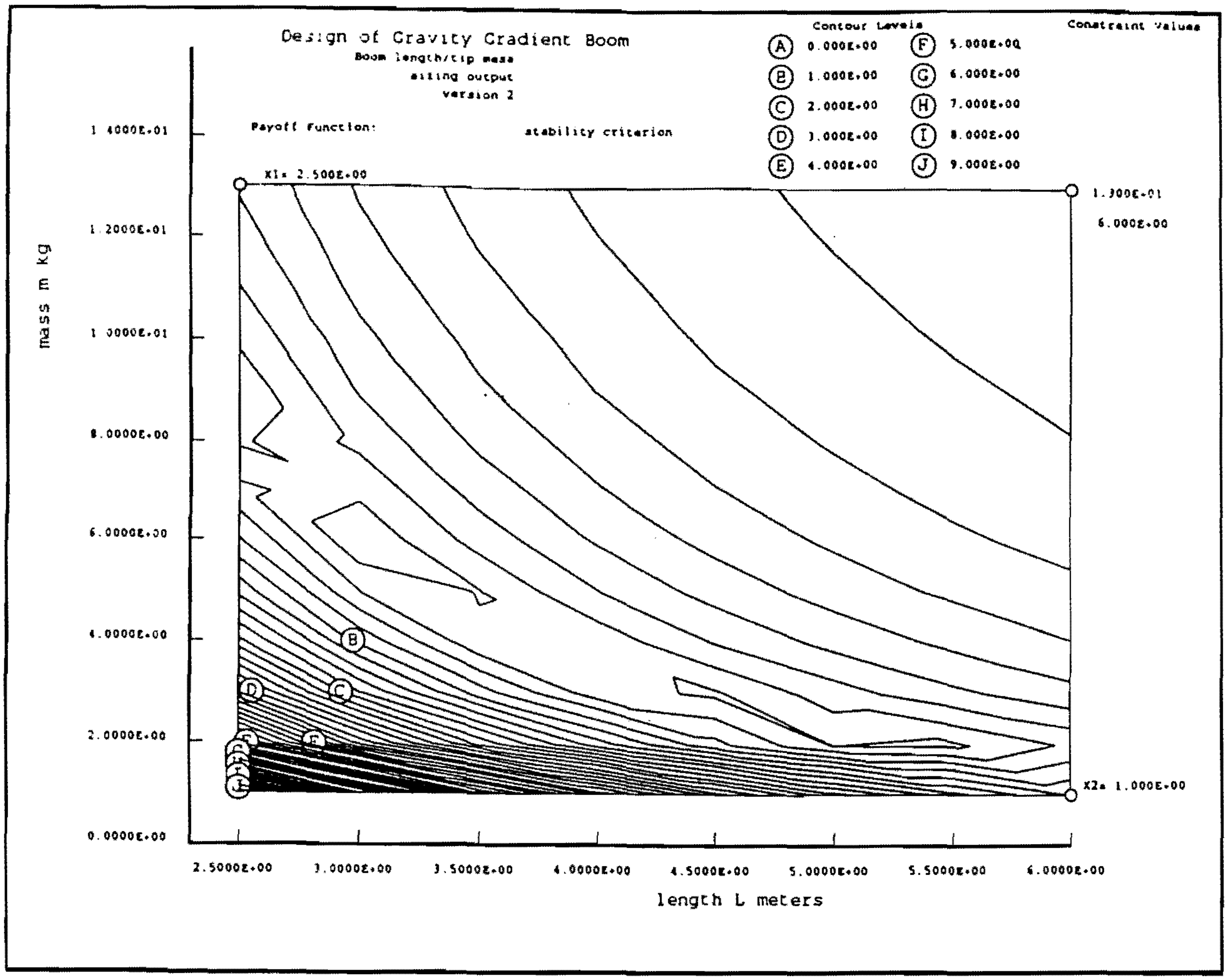

Figure 10. Boom Sizing Contour Plot

Figure 10 shows the contour plot for a stability criterion (Θ_x) of 0.98. Several candidate designs can be seen to meet the desired stability. The final boom size was selected to be 3 meters in length with a 6 kilogram tip mass. This represents almost a fifteen fold increase in I_x.

Stability considerations determined the boom length and tip mass. The diameter and thickness of each section would be determined according to the loads acting upon each section. Loads acting on the gravity-gradient boom were modeled as the Earth's gravitational force acting on the tip mass. A section sizing code was written to size the boom sections based on the known loads, the material properties of graphite-epoxy composites[6], and a selected factor of safety. It was not possible to accurately determine dynamic loads on the gravity-gradient boom due to insufficient source data from the ISAT project, so the factor of safety used in the sizing analysis was increased.

The code was set up to allow the user to choose the desired tip mass and boom length for section sizing analysis. The forces and moment on the boom were then determined based on the user's input of the tip mass and the maximum deflection of the satellite from the vertical axis. Once the user had completed the inputs of number of sections, minimum section thickness, gap between sections, and initial base section outer diameter, the code would size the boom sections. This entailed determining the necessary outer diameters, section thicknesses, and inner diameters corresponding to each boom section. If the section thickness needed was found by the code to be smaller than the minimum input section thickness, the code would substitute in the minimum section thickness and continue the analysis. This measure was included in order to allow for more reasonable composite layup thicknesses in the fabrication process.

Results of section sizing yielded necessary section thicknesses for a number of base section outer diameters. A base section having an outer diameter of 3.81 centimeters was chosen based on the limited volume fraction of ISAT-1 which would be required. Table 1 shows the section sizes in terms of outer diameters, thicknesses, and corresponding inner diameters. It should be noted that in all cases the thicknesses used are the minimum section thickness, and the gap between sections is constant for ease of fabrication.

Boom Section (#)	Outer Dia. (cm)	Section Thickness (cm)	Inner Dia. (cm)
1	3.81	0.102	3.71
2	3.61	0.102	3.51
3	3.40	0.102	3.30
4	3.20	0.102	3.10
5	3.00	0.102	2.90
6	2.79	0.102	2.69

Table 1. Boom Section Sizes

Fabrication Methods

Fabrication methods were developed to produce the necessary sections to conform to the design. This included the construction of suitable mandrels and development of layup procedures. This also included developing a fabrication technique for the section joints.

The mandrels used for curing of the boom sections consisted of two sections of steel pipe, each 0.61 meters in length. The two pipes had inside diameters of were 3.43 centimeters and 3.94 centimeters. These pipes were split along their length at the diameter. These were complemented by three rubber hose sections of 0.76 meters in length. The hoses had outside diameters 2.62 centimeters, 3.15 cenitmeters, and 3.61 meters. This provided the capability to fabricate sections of varying diameter and thickness. The hoses were fitted internally with steel rods along their entire length. Both ends of the hoses were sealed, one containing a valve, to allow pressurization during the curing process.

Each section was fabricated from three plys of woven [0°,90°] graphite-epoxy composite. The composite material was cut to a length of 0.56 meters and a width equal to the circumference of the desired section. The three plys were then debulked with the edges staggered prior to being placed in the mandrel. The debulked composite was then placed in the mandrel and wrapped around the hose. Finally, the pipe section was clamped around it. Bleeder cloth was inserted between the composite material and the outer pipe as necessary to form each section.

With the mandrel clamped together, the inner hose was pressurized to 275,790.3 Pa (40 psi_g), and the mandrel was placed in an oven to cure for 3 1/2 hours at 176° C. Upon completion of the cure, the mandrel was disassembled, and the completed boom section was removed.

To avoid the added complexity and difficulties involved with co-curing the joints along with the respective boom sections, joints from separate cure cycles were epoxied in at a later time. A suitable gas seal was added to each section, and the boom was assembled.

Testing

Once the boom was complete, testing was conducted to ensure that the mechanical performance of the gravity-gradient boom design was satisfactory. The first test to be run was an analytical test involving ANSYS finite-element analysis. The boom was modeled on ANSYS using plate elements. A static analysis was performed. Figure 11 gives a representation of the deflection resulting in a maximum load condition applied to the boom and its tip mass. The boom was found to have a maximum deflection at the tip of 0.05 meters (1.969 inches).

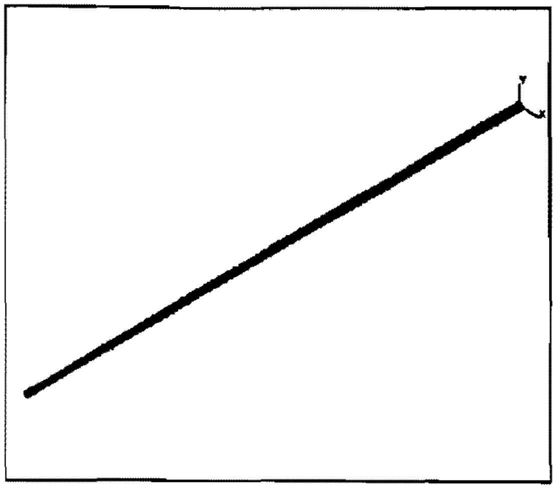

Figure 11. ANSYS Model

Recommendations

Further effort in this subject area is needed to enhance the understanding of the application of graphite-epoxy composites to gravity-gradient booms. The feasibility of the application has been demonstrated. However additional development work and testing is needed to provide the validation necessary to prepare hardware for use in a space application.

Additional testing of the boom section joint to verify the gas seal design and deployability is needed. The magnitude of gas charge needed for deployment in orbit is yet to be determined. Also, laboratory testing of the joint mechanics would serve to validate the length of the joint in respect to the boom sections.

Additional mechanical testing would serve to characterize the composite material properties obtained under the cure conditions used in this project. The repeatability of mechanical properties would build confidence in the production of flight hardware.

Thermal testing is needed to ascertain the optimum ply orientations to minimize thermal expansion coefficients. This testing was not undertaken previously due to inadequate facilities.

Summary

This project has demonstrated the feasibility for use of graphite-epoxy composites in gravity-gradient booms for small satellites. Given the mechanical and thermal properties of graphite-epoxy composites, a boom was designed and fabricated. The boom showed good attitude stability characteristics and encouraging mechanical behavior.

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