A HIGH STIFFNESS BOOM TO INCREASE THE MOMENT-ARM FOR A PROPULSIVE ATTITUDE CONTROL SYSTEM ON FALCONSAT-3

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Abstract. Small satellite missions requiring attitude control can realize significant mass savings by extending the moment arm of a propulsion-based system. Replacing traditional torque rods and reaction wheels with small thrusters on extendable booms can significantly reduce the mass of the ACS. Small satellite buses pose significant integration challenges when incorporating electric micro-thrusters. Generally these satellites have low power capability and small geometries. This impacts attitude determination and control system (ADACS) thruster performance significantly, as it results in low thrust capability (due to power limitations) and small torque moment arms (due to size limitations). To address these technical challenges, the Air Force Research Laboratory is developing a lightweight deployable boom for extending the moment arm of Busek Inc.'s Micro-Propulsion Attitude Control System (MPACS). Specific engineering requirements include increased stiffness, integrated power, and a telemetry wiring harness embedded within the boom's multi-functional structure. A major design goal is to standardize a modular integration with satellites using the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA). Therefore, the boom is designed to stow within the ESPA interface port, a surface region that is generally unused on ESPA satellites. Deployment of the boom is accomplished with a series of elastic-memory composite (EMC) hinges that extend a multi-functional composite structure to a total length of 4 meters. Gravity-gradient stabilization for tip and roll control is abetted by a 6.2-kg tip mass, comprised of the MPACS micro-thrusters and integrated batteries used to power the boom deployment. The boom design effort is currently underway for the United States Air Force Academy's (USAFA) FalconSAT-3 (FS3) satellite, manifested for launch in 2006 as a secondary payload on the MLV-06 Space Test Program ESPA flight.

Introduction

A recent innovation that promises to revolutionize the design of deployable structures has been the development of shape memory materials[1,2]. Shape-memory "mechanisms" can eliminate the need for traditional, highly complex deployment mechanisms, massive stowage containers, and complex deployment controllers. In addition, shape memory mechanisms can lead to dramatically simpler deployable structure designs that include fewer non-structural ("parasitic") parts, making them much more light-weight.

The idea to use shape memory materials to construct a deployable boom is not a new idea. The basic idea, developed and demonstrated in space as early as the 1960's, is to store strain energy within a compact structure; the process of deployment releases this energy until the structure assumes its final, desired shape or configuration. Concepts such as the Storable Tubular Extendible Member (STEM) boom used heat-treated steel to deploy a rigidizable antenna. STEM, now manufactured by TRW, is fabricated to a certain length and then rolled up like a sleeping bag. For longer lengths it is divided into segments, which are joined by a thin lap joint. An alternative and higher performance technology is the Astromast type of boom. This boom is fabricated in its helical deployed configuration, and stored in a coiled configuration in a canister that also acts as a deployment mechanism[4]. This type of boom has extensive flight heritage.

For the FS3 program, Composite Technology Development, Inc. (CTD) is developing and demonstrating an innovative, high-efficiency EMC longeron. This will be the main structural element in a wide variety of simple, mass-efficient deployable boom designs produced by their partner, Starsys Research Corp. (SRC). The proposed EMC longeron is multi-functional in that it provides controllable deployment force and damping, and it is the primary load-carrying element in the deployed boom. In addition, it is mechanically simple, highly reliable, predictable, and highly damped during actuation. This provides a high-precision, repeatable deployment motion with the added benefit of high post-deployment stiffness and strength.

In the following sections, FalconSat-3, the ESPA Ring, and the EMC Boom will be discussed. The focus of the discussion will center on design, performance, and interface issues associated with integrating the EMC Boom with FS3. Topics will include some details of the EMC Boom construction and configuration, as well as the system, schedule, and operational impacts caused by this new payload.

FalconSat-3

FalconSat-3 is a small satellite developed by the United States Air Force Academy (USAFA). See figure 1. FS3 will carry three payloads:

- Plasma Local Noise Experiment (PLANE)
- Flat Plasma Spectrometer (FLAPS)
- μ-Propulsion Attitude Control System (MPACS)

The EMC Boom development is of particular interest to the MPACS, a very fuel-mass efficient electric thruster. MPACS, built by Busek, Inc., weighs approximately 2.1 kg, and it can deliver a 25 μN•s impulse within its 2-5 μs firing time. In order to further demonstrate the usefulness of the deployable boom concept, a single MPACS thruster will be mounted at the end of the EMC Boom. When deployed, this will increase the thruster's actuation authority by more than an order of magnitude; in addition, the extended boom will provide gravity gradient stability for the other payload experiments. It is clear how such a boom-thruster configuration has the potential to open up the small satellite systems design space considerably. The stowed boom package attaches to the bottom of the FS3 bus; its stowed dimensions are small enough for it to fit through a single port on the ESPA ring.

Figure 1: FalconSat-3 with EMC Boom and MPACS thruster mounted on bottom plane

A Lightband deployment mechanism, supplied to USAFA by Planetary Systems Corporation, will release FalconSat-3 from the ESPA. In addition, launch loads will be reduced by inserting CSA Engineering's Shock Ring between the Lightband and the ESPA. Lightband and the Shock Ring are both AFRL technology development efforts. FS3, along with a number of other ESPA-integrated payloads, are scheduled for launch on the MLV-06 mission.

ESPA Ring

As shown in figure 2, The Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) ring is an aluminum cylinder that is 5 feet in diameter and designed to help launch small satellites into space. This ring can carry up to seven loads: one primary load weighing up to 15000 lbs and six secondary weighing 400 lbs each[6,7]. The primary load sits atop the ring while the six secondary loads connect to the interface through the six holes along the outer surface of the ring.

In order to deploy FalconSat-3 into its final orbit, the ESPA ring will provide the required interface. FalconSat-3 will connect to the ESPA ring, via the Lightband deployment mechanism, through one of the six ports along the sides. In the launch configuration, the boom's cylindrical canister and thruster will extend through the opening into the ESPA's central region.

Figure 2: ESPA Ring

Figure 3: Stowed configuration with batten frame

EMC Boom

Elastic Memory Composite materials are a relatively new addition to the family of shape memory materials[4]. The key advantages of EMC materials over shape memory alloys and shape memory ceramics are their substantially lower densities, higher strain capacities, and higher damping ratios. Hence, EMC materials exhibit many favorable qualities for deployable space structures; as such they have piqued a broad interest within the deployable space structures industry.

The boom (longeron) itself will be constructed using CTD's special TEMBO™ product line of EMC materials[5]. Two EMC tapes (resembling carpenter tapes) will form the longeron. Once fabricated to their final length of four meters, the tapes will be heated and S-folded so as to fit within the designed deployment container. The composites will then be "frozen" into that shape (i.e. reduced to room temperature) while retaining a memory of their initial shape. See figure 3. Conductive wires embedded in the composite allow for the material to be re-heated. When the appropriate level of heat is reapplied, the composite tapes will want to unfurl and regain their original shape, thereby releasing the stored strain energy.

The two tapes are curved along the main axis, like carpenter tapes. As such, there are two configurations that can be used to form the longeron: concave out) (and concave in ( ). The "concave in" configuration was chosen due to the increased stiffness properties of the structure seen in initial analyses. This configuration forms a natural cylindrical cavity along the main axis of the longeron; moreover, there is a central guide rod that aids the deployment phase, and so the "concave in" configuration allows for superior performance while reducing mass inertia, as the tapes hug the guide rod closely rather than curving away from it.

Batten frames will augment the stiffness of the boom in its deployed state. See figure 4. These battens also prove useful in the stowed configuration, where they secure sections of the EMC tapes to the central guide rod. This restricts the range of motion that can be achieved while subjected to launch loads. Boom tape guides are also in place along the frames to aid in stowing and securing the tapes. When deployed, the batten frames will be surrounded by the tape elements, ensuring that support loads will be properly transferred.

The EMC longeron connects to a base plate at one end and an end-mass assembly at the opposite end. The base plate serves as the mechanical interface with FalconSat-3; the end-mass assembly, designed and integrated by SRC, includes the stowage cylinder, batteries, deployment control electronics, and a mounting platform for the MPACS thruster.

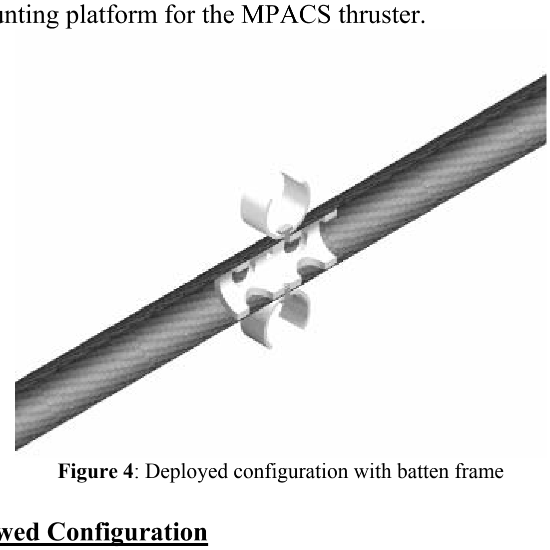

Figure 4: Deployed configuration with batten frame

Stowed Configuration

The boom will be stowed in a cylindrical container with the MPACS thruster seated on top, as shown in Figure 5. The EMC tapes will be folded within the can in a snake-like "S" pattern. Each folded tape will be attached to the central support on their respective sides of the can. A *Qwknut* separation device, an AFRL-developed technology described in the following section, will be placed along the centerline of the cylindrical container in order to minimize possible tip-off dynamics during deployment. A cup/cone interface will be used at the boundary between the cylinder's bottom and the base plate. This will further constrain potential motion between the boom assembly and FS3.

Also within the cylinder, there is enough volume to mount at least eight 5 A-h NiCd rechargeable batteries, complete with power conditioning circuitry (if required). There is also mounting space available for the deployment control and telemetry electronics. The batteries and power conditioning electronics provide a local, dedicated power source for any experiment or components mounted on the cylinder. It also prevents the need to run heavy-gauge power cables up the EMC longeron. Furthermore, since batteries normally account for appreciable amounts of mass, by placing them within the end-mass canister they have a multi-functional purpose: they aid significantly in providing gravity-gradient stability. For the FS3 mission, the battery pack provides power for the MPACS thruster.

Figure 5: Complete stowed configuration cut-away

Available mounting area limits the quantity of extra electronics that may be mounted within the canister. In addition, there is a limit on the number of "service" wires (power, ground, command & data, etc.) associated with the mounted experiment or component. Service wires must be run along the edges of the EMC tapes, and so too many wires can hamper the boom's ability to deploy. What constitutes "too many" wires depends in part on wire gauge and thermal properties.

The EMC Boom's stowed package dimensions fit within a cylindrical region 11 inches in diameter and 10.2 inches in height. The MPACS thruster fits within the circular profile; when added to the Boom system with its special mounting bracket, it extends the total packaged height dimension to 15.7 inches.

Separation Device

SRC's *Qwknut* separation device will be used to deploy the boom. This device consists of a pre-stressed screw whose load path passes through the center of the cylinder. When heat is applied, the screw will fracture, allowing for separation between the cylinder and mechanical base plate to take place. This method of separation occurs at a low speed and places minimal stresses (low shock) on the rest of the system.

The Qwknut device holds the tip mass to the mechanical base of FalconSat 3. It also helps to contain the boom tapes prior to deployment. Prior to launch, a "remove before flight" mechanism will be added to keep the canister from separating prematurely. This device is yet to be determined.

Deployed Configuration

The boom will extend to 4 meters when deployed, with the MPACS thruster and cylinder located at one end and FalconSat-3 located at the other. Current estimates show that the end mass will be approximately 7 kg, as opposed to FS3's mass of roughly 42 kg. As such, the new system center-of-mass will lie approximately 0.4 meters along the length of the boom (as measured from FS3). The new moment arm for the MPACS thruster will therefore be about 4 meters.

The act of deploying the EMC Boom follows a basic sequence of events:

1. The host satellite (FS3) sends a simple "deploy now" signal to the Boom, which activates the deployment control circuitry.
2. Control circuitry activates EMC tape heaters; built-in thermal sensors let the control circuitry know when the critical temperature is achieved.
3. Control circuitry activates the Qwknut release mechanism. The end mass is released; the guide rod and cup-cone interface constrain off-axis motion and rotation.
4. The Boom deploys and rigidizes as the tapes release their strain energy.
5. Once fully deployed, a mechanical limit switch is automatically tripped; this shuts off the tape heaters and returns a "deployment complete" signal to the host.

This sequence of operations has some dependency on the larger set of satellite mission operations, and will be adjusted/modified accordingly for the FS3 mission. This is not anticipated to pose a problem, as there is a great deal of operational flexibility in the basic sequence of events.

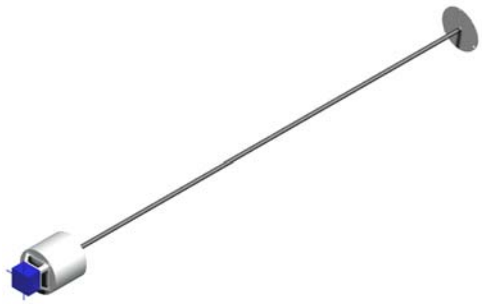

Figure 6: deployed configuration

Once the boom is fully extended and the heat source deactivated, the boom will "freeze" in its deployed state. Two of the service wires running up the Boom are power lines that feed the end-mass battery pack. A trickle charge along these lines will allow the FS3 power supply to replenish the batteries so that they can supply high-margin power for MPACS operations.

System Impacts

Adding the EMC Boom with the MPACS thruster to FS3 will produce a number of system-level impacts. Mechanically, adding the EMC Boom system will require an extra structural interface. Bolt patterns and other holes must be arranged so that there is no interference with other FS3 components or the Lightband deployment mechanism. In addition, the Boom system will alter the mechanical properties of the FS3 launch configuration, including the center-of-mass, mass inertias, and first-mode vibration frequency values. Upon deployment, the dynamic behavior of the EMC materials in the orbital environment (as well as outgassing behavior) is generally unknown, although theoretical models exist.

In terms of electrical impacts, the number and gauge of service wires running up the Boom will need to be carefully controlled so that the EMC tapes will deploy properly. Routing for the service wires between the Boom base plate and the FS3 electrical bus is also an issue. The nature and required complexity of the deployment and power conditioning electronics is a major concern. Finally, the entire system needs to be analyzed and functionally tested for EMI, mainly in order to ensure that the MPACS thruster will operate as intended after deployment.

The impacts on mission operations will occur primarily during the deployment phase. Total deployment time is critical in that it affects how long other satellite resources must be dedicated to monitoring the deployment process. Furthermore, the deployment time needs to fit within a single contact window so that the entire deployment process can be monitored; to not do so introduces a degree of risk against achieving other mission goals. The EMC tapes may be heated in stages or all at once; for a 4 meter Boom length, it will take roughly 5-10 minutes for the composite material to heat up adequately and evenly. This length of time is determined in part by the material strain-rate limit[1]. If released first and then heated in stages, it will therefore take 5-10 minutes for the Boom to deploy completely; if pre-heated for 5-10 minutes prior to release (as is the plan for FS3), it will take less than 30 seconds for the entire longeron to deploy upon release. Even so, since FS3 will be delivered to LEO, contact times will fall within the given range, making timing a significant issue. In addition, the Boom imposes specific constraints on the dynamic window for deployment. The attitude angles and angle rates must be within certain limits or else the boom will deploy and/or stabilize motion in the wrong direction (nadir vs. zenith). As such, careful mission planning will be a necessary outcome of the Boom integration exercise.

A number of specific satellite subsystems are affected by the EMC Boom's presence. The subsystems affected are the power, command and data handling (CDH), attitude determination and control subsystem (ADACS), communications, and thermal subsystems. The power subsystem is affected since the trickle charge that feeds the Boom's supplementary battery supply leeches power resources from the rest of the satellite. In addition, this power feed may need to be monitored for faults. Initial analysis shows this to be a manageable issue.

The CDH and communications subsystems are affected in that extra commands and telemetry must be processed and communicated with the ground. One of the mission goals for the Boom system will be to characterize its behavior on orbit, which may require an abundance of thermal, strain, and accelerometer data. Processing the few extra commands is anticipated to be straightforward; however, the quantity of sensor data returned may have an effect on CDH memory reserves. Such an abundance of Boom telemetry may also exceed the communication subsystem's ability to download all data, given a daily ration of ground contacts. Adequate trade studies will prevent these issues from emerging as design drivers.

The ADACS subsystem is probably affected the most by the Boom. First, the moment arm of the MPACS thruster is extended to 4 meters, versus the 0.25-meter moment arm achieved by mounting the MPACS directly to FS3. The result is that the relative torque actuation authority is increased by a factor of 16.

Thus, for a given maneuver, the thruster will use roughly 94% less fuel, and may be fired with a greatly reduced duty cycle. The gravity gradient effect produced by the boom will be significant also, as the new mass distribution will result in a max/min inertia ratio of more than 60. It should be noted that redistributing the mass comes at a price: while the available torque increases, the greatly increased mass distribution reduces the overall maximum angular acceleration by 80%. Therefore, attitude control response times are much slower.

In terms of the thermal subsystem, heat transport along the boom is a potential issue. The boom can act as a heat-conducting rod in either direction, transporting heat away from FS3 or the MPACS thruster, depending on the given thermal distribution. This effect needs to be evaluated and adequately modeled.

Development Schedule

In order to meet deadlines for FS3's 2006 launch date, a moderately aggressive schedule will be followed. The integrated design package for the EMC Boom system will be completed by the end of September 2003. At this point the design will be at a CDR level, with some conceptual hardware and models completed. By January of 2004 a mass model will be completed and delivered to USAFA for integration and preliminary testing. The flight unit will be completed and delivered by October of 2004, at which point USAFA plans to integrate and begin final testing for FS3. During the January-October interim, a number of possible component-level tests are being planned, including a "zero-g" EMC tape deployment test aboard a KC-135 aircraft.

Summary

Recent advances in shape memory materials have led to the development of elastic memory composites. These EMC's have a wide variety of applications, as they can be used to construct simple, reliable, and predictable mechanisms that are lightweight and have a low part-count. Such mechanisms are of great interest to a number of commercial interests and government agencies, such as AFRL. Composite Technology Development, Inc., together with their partner Starsys Research Corp., have developed a compact, low-cost deployable boom system which features specialized EMC tapes as the primary boom longeron components. This EMC Boom system design can supply gravity gradient stability for microsatellites, as well as an isolated, self-powered platform for conducting experiments or operating specialized components.

The Boom that has been designed for use on FalconSat-3 will provide a platform to extend the moment arm of Busek Inc.'s MPACS thruster. This benefit, augmented with gravity gradient stability, greatly enhances FS3's attitude control system in its support of other mission payloads. In return, the FS3 mission will provide the EMC Boom system some flight heritage and an opportunity to characterize boom dynamics both during deployment and in the fully deployed state. This will supply information and reduce risk for other microsatellite missions interested in employing this very useful technology.

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