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14. ABSTRACT
Future small spacecraft will have a need for lightweight, highly reliable, and cost-effective mechanisms for the deployment of radiators, solar arrays, and other devices. To meet this need, Composite Technology Development, Inc. has developed TEMBO® Elastic Memory Composite (EMC) materials, which accommodate very high folding strains without damage, while providing very high deployed stiffness- and strength-to-weight ratios. Over the past few years, CTD has developed and performed extensive ground testing on a TEMBO® EMC deployment hinge for radiators, solar arrays and other deployable spacecraft components. The present paper will discuss the details of two flight experiments to validate the TEMBO® EMC hinge design on-orbit. In particular, the paper will discuss: 1) detailed design of the flight hardware for both experiments; 2) ground-verification and acceptance testing of the flight hardware; and 3) status of the flight missions.

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Qualification of Elastic Memory Composite Hinges for Spaceflight Applications

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Future small spacecraft will have a need for lightweight, highly reliable, and cost-effective mechanisms for the deployment of radiators, solar arrays, and other devices. To meet this need, Composite Technology Development, Inc. has developed TEMBO® Elastic Memory Composite (EMC) materials, which accommodate very high folding strains without damage, while providing very high deployed stiffness- and strength-to-weight ratios. Over the past few years, CTD has developed and performed extensive ground testing on a TEMBO® EMC deployment hinge for radiators, solar arrays and other deployable spacecraft components. The present paper will discuss the details of two flight experiments to validate the TEMBO® EMC hinge design on-orbit. In particular, the paper will discuss: 1) detailed design of the flight hardware for both experiments; 2) ground-verification and acceptance testing of the flight hardware; and 3) status of the flight missions.

I. Introduction

Future small spacecraft will have a need for lightweight, highly reliable, and cost-effective mechanisms for the deployment of radiators, solar arrays, and other devices. To meet this need, Composite Technology Development, Inc. has developed TEMBO® Elastic Memory Composite (EMC) materials, which accommodate very high folding strains without damage, while providing very high deployed stiffness- and strength-to-weight ratios.[1] In recent years, TEMBO® EMC materials have been used to design a wide variety of innovative deployment mechanisms and structures with improved reliability and performance, lower mass, and reduced deployment shock compared to traditional deployment mechanisms.[2]

In an early effort to explore the application of TEMBO® EMC materials to deployment mechanisms, CTD developed a prototype TEMBO® EMC deployment hinge for radiators, solar arrays and other deployable spacecraft components.[3] Initial feasibility of the TEMBO® EMC hinge concept was established through the design, fabrication, and ground testing of a drop-in-replacement hinge for shape memory alloy hinges on the NASA New Millennium Program (NMP) Lightweight Flexible Solar Array (LFSA). Several subsequent iterations of the TEMBO® EMC hinge design have been made to improve all aspects of its performance, and each iteration has been verified through hardware fabrication and testing.[4]

The current TEMBO® EMC hinge design is shown in Figure 1(a). The key components of the hinge are two semi-cylindrical TEMBO® EMC laminates with embedded heaters for actuation, and two end fittings for interfacing with the deployable structure. Figure 1(b) shows a photograph of a TEMBO® EMC hinge bent and frozen into its packaged shape. During deployment, the TEMBO® EMC blades straighten along their length and re-assume their circular cross section shape to "lock" into their final deployed shape (Figure 1(a)). The deployment motion is controlled and well-damped due to the inherent viscoelasticity of the TEMBO® EMC material during actuation.

CTD has developed two spaceflight experiments to qualify TEMBO® EMC hinge technology. The first mission will be the first flight of an EMC component and is the Air Force Research Laboratory (AFRL)-sponsored Elastic

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Memory Composite Hinge (EMCH) experiment that will validate operation of six TEMBO® EMC hinges in the shirtsleeve, zero-g environment of the International Space Station. The second mission will be the first flight of an EMC component in a non-critical structure, and is a pair of TEMBO® EMC hinges to deploy an experimental solar array on the TacSat-2 Mission. The present paper will discuss the details of the EMCH and TacSat-2 flight experiments to flight-validate TEMBO® EMC hinge technology. In particular, the paper will discuss: 1) detailed design of the flight hardware for both experiments; 2) ground-verification and acceptance testing of the flight hardware; and 3) status of the flight missions.

(a) Deployed configuration. (b) Packaged configuration.

Figure 1. TEMBO® EMC hinge.

II. EMCH Flight Experiment

The goal of the EMCH flight experiment is to validate the robustness of TEMBO® EMC hinges to deploy in off-nominal conditions in zero-g. In addition, this experiment will study degradation due to storage and repeated operation in the International Space Station (ISS) environment. The specific objectives are to determine the accuracy, repeatability and the stability of TEMBO® EMC hinge deployment under various thermal-loading conditions, and to verify the deployment of a TEMBO® EMC hinge against a resistive torque. The EMCH experiment is self-contained in a housing that occupies the volume of a full EXPRESS rack locker (see Figure 2). The EMCH experiment is designed to be operated outside the locker (inside the ISS pressurized crew modules) by ISS crew, and requires power, videotape recording, serial data connection, data downlink, and crew interaction for operation.

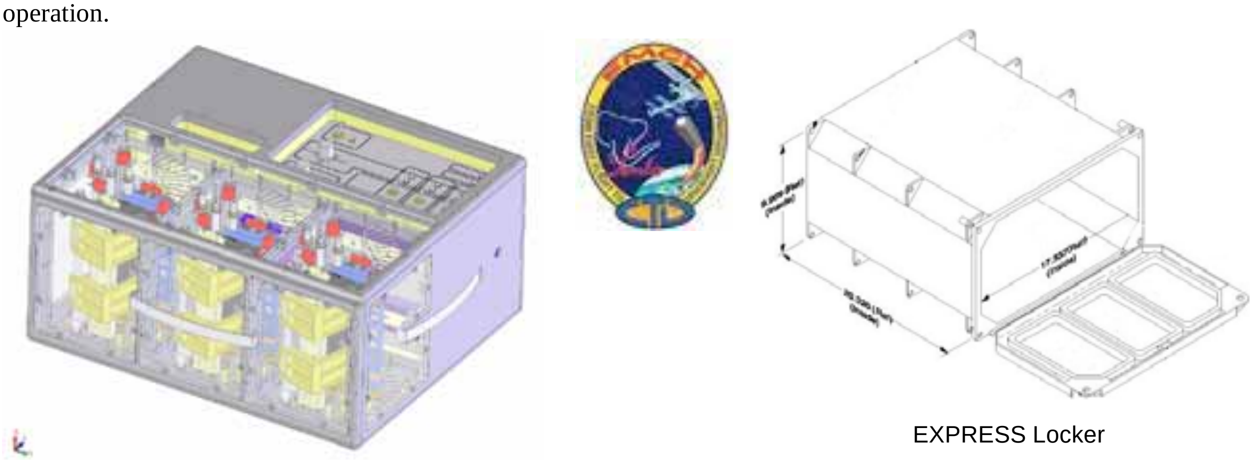

Figure 2. EMCH Experiment.

The EMCH experiment contains six TEMBO® EMC hinges, each approximately 10-cm by 2.5-cm by 2.5-cm in size (see Figure 1), assembled into three test article subassemblies containing two hinges each. The test article subassemblies will be deployed through crew actuation, while their torque-rotation history and deployment accuracy are recorded automatically. Each test cycle starts with the astronaut crew folding the hinge test articles using tooling and procedures provided with the experiment. Then, the crew will deploy the test articles and record data. This test cycle will be repeated many times throughout the ISS mission. The components of EMCH are described in the following paragraphs.

A. Housing

The external housing is a six-panel frame fastened at the panel perimeters. There is a Lexan™ window over the test subassemblies. The top surface has a recessed switch panel and a recessed tool holder. The left side of the box has a recessed area for the power and data connectors and the fuse box. Other than the switch panel and the Lexan™ window, all the materials are machined aluminum.

B. Control Panel

Figure 3 shows a sketch of the EMCH control panel. There is a pull-lock toggle switch and LED indicator for main power and there is a red LED showing electrical or ground fault. There is a three-position, pull-lock switch for each test assembly. Switch positions in either the “Deploy” or “Reset” position send current to the hinge heaters. Current flow is indicated by the green LED’s labeled “Power”. When the hinge has reached the set point temperature, the amber “Temperature” LED is lit. Rotary switches control the set-point temperature for each heater string. These switches are nine-position deck switches with detents for each position.

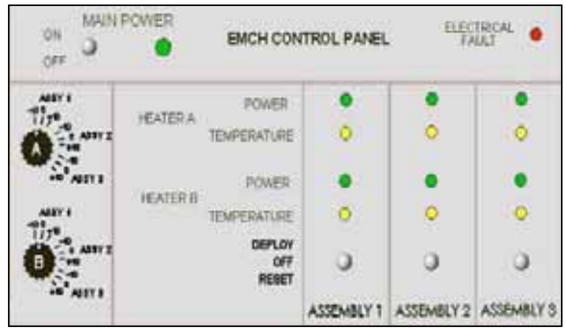

Figure 3. Control panel layout.

C. Test Subassemblies

Figure 4 and Figure 5 show the test subassemblies. There are three subassemblies, each with two TEMBO® EMC hinges fixed at one end to the EMCH housing and connected to one another at their free end by a machined plate, referred to as a *panel simulator*, which constrains the hinges to move in a coordinated fashion like they would if they were deploying a solar array or radiator panel. Each subassembly is held with its own aluminum frame that includes a Lexan™ window on top for ease of viewing. Protractors are installed on the top and bottom face of each subassembly box to provide a reference to determine angular and radial position versus time as the pair of hinges deploy. There is an indicator at the top and bottom of the panel simulator that moves relative to the protractors during deployment. Video of each deployment will indicate position versus time.

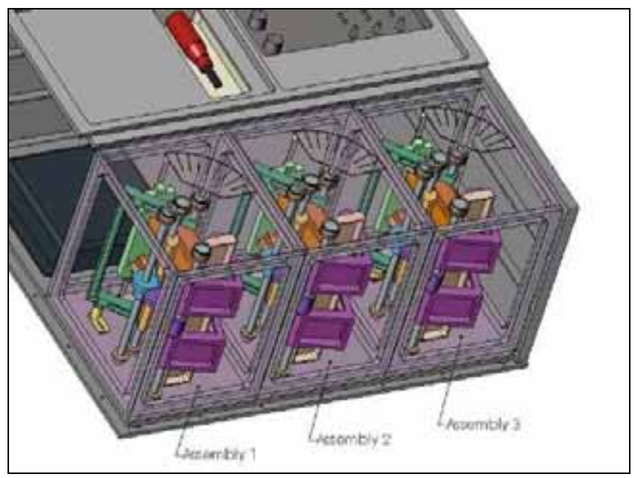

Figure 4. Test subassemblies.

The hinge heaters in each subassembly are wired into two separately controlled circuits, or *heater strings*, to allow differential heating of the hinges to mimic off-nominal deployment conditions that might be encountered in operational installations of the hinge. All three subassemblies are identical except for the heater-string wiring. In subassembly 1, heater string A includes both tapes of the upper hinge and heater string B includes both tapes of the lower hinge. In subassembly 2 heater string A includes both tapes on the left side and heater string B includes both tapes on the right side. Finally, subassembly 3 is identical to subassembly 1 with the addition of a constant-force torque spring to resist the deployment of the hinges.

The hinges are re-packaged manually by the astronauts with a flatten-and-fold mechanism that is included in each subassembly (see Figure 5). Flattening and folding of the hinges is accomplished using two cam shapes that are coordinated with spur-and-sector gears through a single astronaut-tool interface. The cams are identified as a pinching cam and a folding cam. The folding cam is on a swing arm that allows the cam to retract from the folded hinge without any hinge interference. The swing-arm interfaces with a detent in both the folded and retracted positions. The cam surfaces are Ultem™, the shafts and gears are 316 stainless steel, the cam swing arm is aluminum. Once the hinge tapes are flattened, the hinge can be folded. The folding swing arm will be driven by the astronaut and will engage the panel simulator and push it approximately 90 degrees to package the hinges.

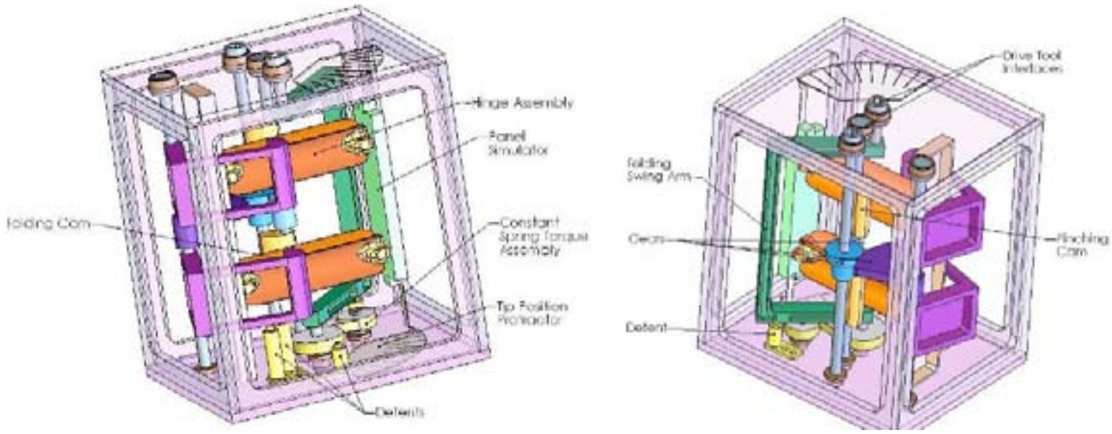

Figure 5. Test subassembly 3 with torque resistance.

D. Ground Verification and Acceptance Testing

The completed EMCH flight unit is shown in Figure 6 an identical *training unit* was built for astronaut training and functionality testing. Three sets of six TEMBO® EMC hinges each (18 total) were fabricated for the EMCH experiment: one set of flight hinges, one set of training-unit hinges, and one set of control hinges. Axial stiffness was measured for the flight and control hinge sets. Upon return of the experiment, axial stiffness will again be measured for both sets of hinges and the data will be compared to determine if any mechanical property degradation occurred over the numerous package-and-deploy cycles on-orbit. Figure 7 shows a typical load-displacement curve for one flight hinge. The control set of hinges will also be used as spares should any problems arise with the flight hardware prior to turnover.

Figure 6. Completed EMCH flight unit.

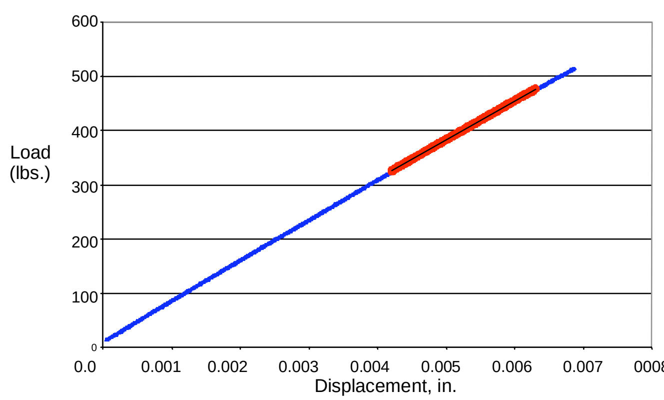

Figure 7. Load/displacement curve for one flight hinge.

Two full runs of the proposed on-orbit experiment matrix (26 total fold-and-deploy actuations) were performed, using the training set of hinges. The hinges successfully completed both experimental runs and no damaged was observed upon inspection. The flight hinges have been functionally tested and folded/deployed at least once in their respective assembly.

Before delivery to the Air Force Space Test Program (STP) Office, the EMCH flight unit was vibe tested by CTD. The purpose of the vibe test was to verify structural integrity and workmanship. The vibration profile enveloped any possible mounting location for Shuttle or ATV. Figure 8 shows the test setup for the X-axis vibe test and the X-axis control plot from vibe testing. After the vibe test, the flash memory card was observed to be loose from the data logger, but all systems were otherwise functional. Subsequent functional tests verified there were no electrical or mechanical system failures. The flash card ejection problem was solved with a small clamp attached to the side of the data logger. The card cannot be removed with the clamp in place.

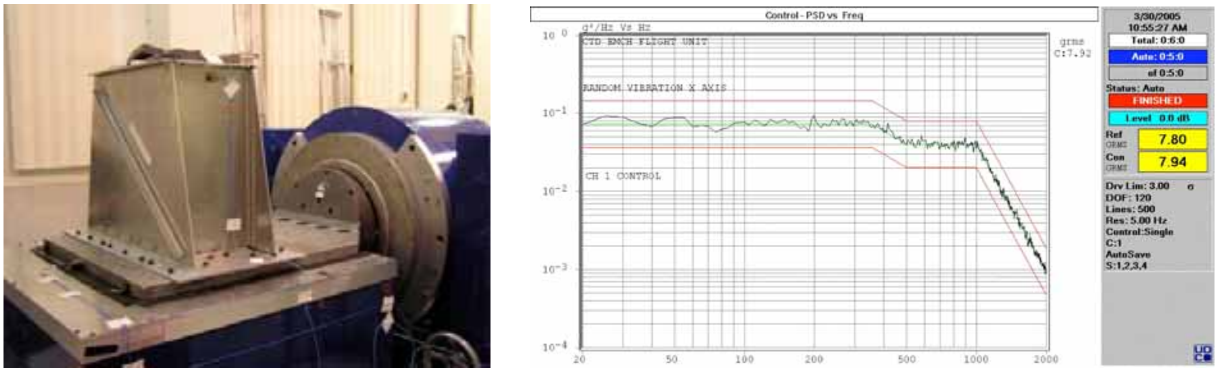

Figure 8. Test set-up and control plot for x-axis vibe test.

At the present time, EMCH is continuing to go through NASA acceptance testing and is gaining final approvals for flight. As of early December, 2005, EMCH had passed off-gas and software-verification testing, and crew-procedures verification. The NASA Phase III Safety Review is pending approval on two minor comments to the safety package. EMI testing uncovered two minor electronic anomalies, and the flight hardware is currently being reworked to correct these problems. EMCH will be re-tested for the EMI verification. Also, the ATV-1 launch has continued to slip, and STP is now looking for alternative launch opportunities, including a shuttle launch in the fall of 2006. As a result of this slip the crew training for EMCH has been rescheduled for 2006. EMCH is currently being reviewed for manifest on STS-116, increment 12A.1, scheduled for October of 2006.

III. Solar Array Hinges for TacSat-2

The TacSat-2 mission will be the first flight of TEMBO® EMC hinges in a non-critical deployable structure. TacSat-2 is a 837-lb_m satellite being developed by AFRL to demonstrate several new spacecraft technologies of interest to the Air Force, including advanced solar array technologies. The Experimental Solar Array (ExpSA) on TacSat-2 will provide flight heritage for TEMBO® EMC hinges and for the MicroSat Systems, Inc. (MSI) Foldable Integrated Thin-Film Stiffened (FITS)[5] solar array deployment system. ExpSA consists of two experimental FITS solar arrays deployed off of the two main spacecraft solar arrays (see Figure 9). The ExpSA arrays are identical, with the exception of the hinges connecting them to the main array. TEMBO® EMC hinges are used on one wing, and conventional torsion-spring hinges (labeled "MSI Hinges" in Figure 9) are used on the other to provide deployment force between the main solar array and the ExpSA solar arrays. Power produced by the ExpSA solar arrays will enhance the TacSat-2 mission, but is not critical to mission success.

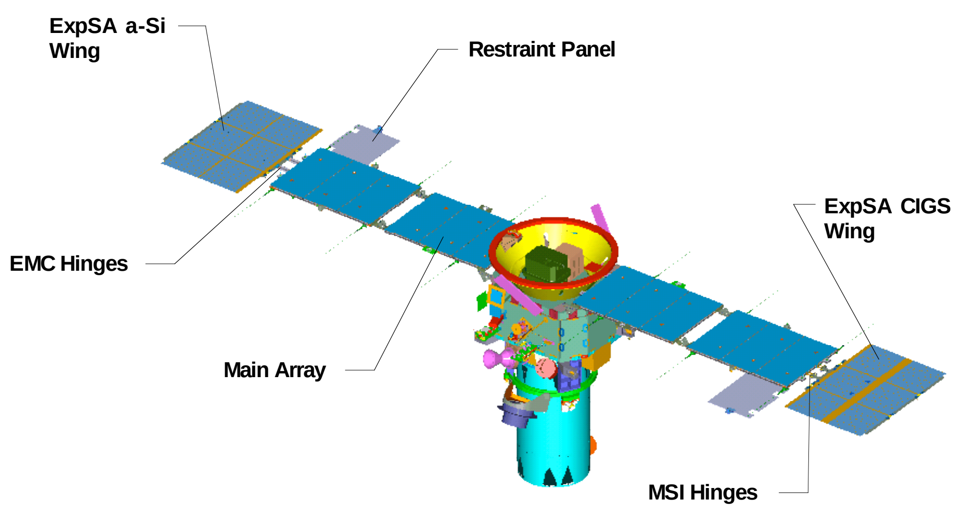

Figure 9. TacSat-2 ExpSA experiment.

A. Integration of Hinges onto TacSat-2 Spacecraft

The TacSat-2 ExpSA TEMBO® EMC hinges are essentially identical to the hinges flown on EMCH (see Figure 1). The flight hinges were delivered to MSI on December 30, 2004 (one is shown in Figure 10 for spacecraft integration). One notable observation made by MSI during integration was that the TEMBO® EMC hinges alleviated a tolerance stack-up issue that was found on the conventional torsion-spring hinges (labeled MSI hinges in Figure 9 and shown close-up in) used to deploy the second FITS array. Tolerance stack-up in that array assembly resulted in the conventional hinges not fitting together when it was packaged. To compensate for this, MSI had to disassemble and re-machine some of the components. A similar tolerance stack-up issue existed on the solar array with the TEMBO® EMC hinges, but when this array was packaged, the packaged EMC hinges were compliant enough to easily allow the solar panels to move as needed and fit together nicely, despite the tolerance stack-up. Once deployed, however, the EMC hinges held the solar panel in a very precise position.

For the TacSat-2 installation, the TEMBO® EMC hinges are wrapped in a single layer of aluminized polyimide thermal shroud, as shown in Figure 12. This barrier reduces radiative heat transfer losses to the space environment while the hinges are being heated for deployment. The thermal shrouds were installed after the initial deployment testing, so that the hinge could be easily observed during the initial tests. After installation of the shrouds, testing was performed to ensure that the they did not present a snag hazard or prevent deployment in any way. Additionally, the gravity-off-load deployment tests, discussed in this paper, were performed with the thermal shrouds installed, and no problems noted.

Figure 10. TEMBO® EMC flight hinge shown integrated onto ExpSA and packaged.

Figure 11. Conventional torsion-spring hinges for ExpSA.

Figure 12. TEMBO® EMC hinges with thermal shrouds installed.

B. TacSat-2 ExpSA Assembly Random Vibration Testing

Random vibration testing was performed on the ExpSA flight hardware by the University of Colorado (CU) Center for Aerospace Structures (CAS) at Ball Aerospace & Technologies Corp. (BATC), Boulder, Colorado, under contract to MSI. The test setup is shown in Figure 13. The system was fastened to an interface plate that was geometrically equivalent to the main array that the ExpSA will interface with in the flight system (see Figure 9). The vibration spectrum used for this testing was was 9.2g RMS. The vibration testing was successfully completed with no noticeable damage. Additional deployment and functional testing was completed after the vibration testing, verifying that no electrical or mechanical damage occurred.

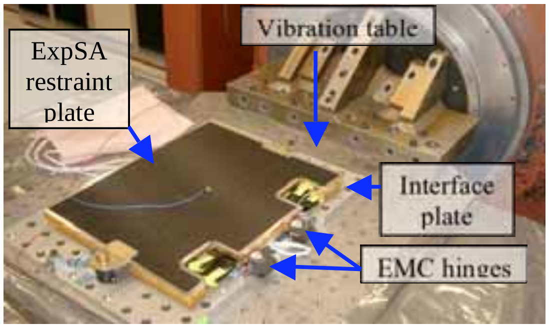

Figure 13. Random vibration test setup for ExpSA system with TEMBO® EMC hinges.

C. TacSat-2 ExpSA Deployment Testing

CU performed the ExpSA deployment testing in the CAS laboratory under contract to MSI.[6] Dr. Jason Hinkle and Joni Jorgenson designed the gravity-compensated test fixture (as shown in Figure 14) and protocol for the deployment testing. The test system is composed of three main components. The first is a rigid, level mounting structure (see Figure 14) that the ExpSA interface plate is mounted to. The second is a set of two Kevlar cables that are attached at the center of mass of each z-folded section. These cables are supported by a very low stiffness linear spring, and are attached to a fixed pivot point approximately fifteen feet above the top of the panel. This point is located on the rotational axis of the root hinges, thus insuring that the gravity compensation system induces no moments about this axis. The third component of the test system is a videometry data acquisition system to record the motion of reflective targets placed on the ExpSA during the deployment.

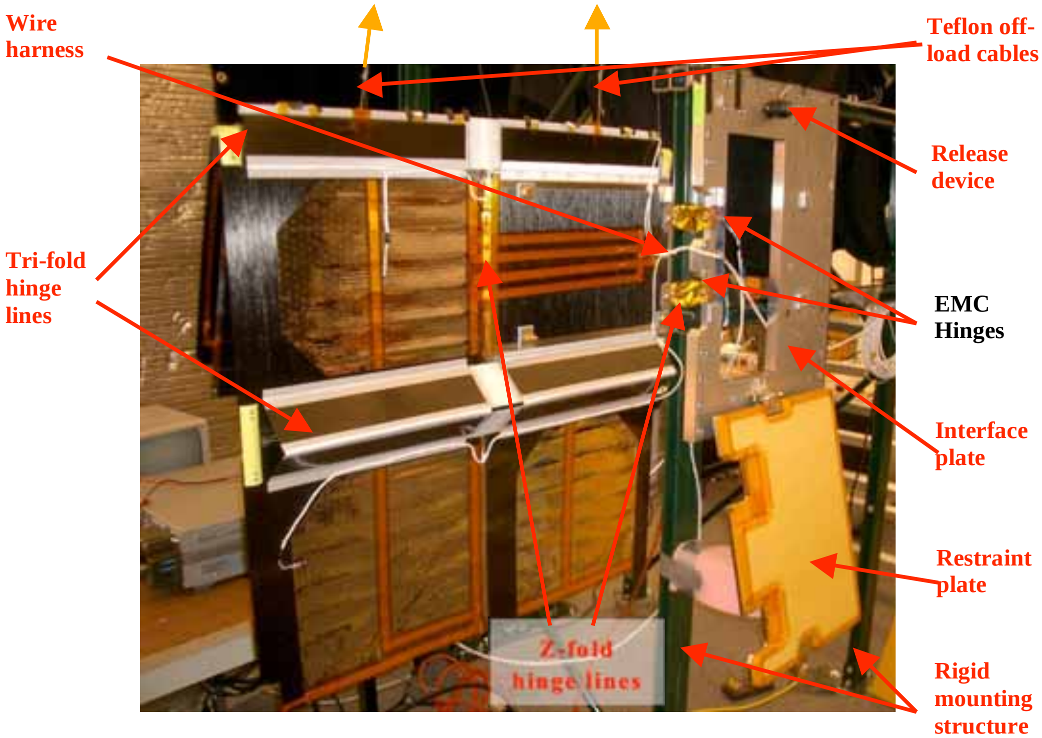

Figure 14. ExpSA deployment testing.

Three deployment tests were conducted to verify the functionality of the system. In all three tests a DC power supply (set to the proper voltage to mimic the supply power from the TacSat-2 spacecraft bus) was used to power the TEMBO® EMC hinges. The first deployment test was done at room temperature and allowed only the z-fold hinge lines of the ExpSA to deploy, while constraining the tri-folded panels (see Figure 14) such that they could not deploy. By locking out the tri-fold panels, this test was focused on only the first two stages of deployment: release of the restraint plate, and deployment of the TEMBO® EMC hinges and the z-fold hinges. This deployment was gradual, resulting in very low end-of-deployment shock (as desired), and positive locking of the solar array. This test scenario was repeated three times with similar results.

The second deployment test was the same as the first, except that the tri-fold hinge lines were not restrained, which allowed the lower tri-fold panels to deploy downward with gravity. The upper tri-fold panels did not have enough deployment force to overcome gravity and thus did not deploy. This test scenario was successfully repeated twice at room temperature. Figure 14 shows the array at the end of one of these deployments. The third deployment test was the same as the second, but conducted with the ExpSA assembly pre-cooled to a nominal temperature of -40°C using liquid nitrogen. This test also demonstrated successful deployment of the TEMBO® EMC hinges.

D. TEMBO® EMC Hinge Deployment Torque Verification

The deployment-torque-output requirement for the TEMBO® EMC hinges was derived from the maximum hindering torque created by the wire harness that runs across the hinge line (see Figure 12). The wire harness design was specified by MSI, but the maximum hindering torque created by this wire harness was not specified. Therefore, CTD performed hindering-torque testing on samples of the wire harness, and torque-output testing on the TEMBO® EMC hinges to verify adequate torque margin. This torque testing was done at CTD's facility using a test apparatus designed for pure-torque testing of flexible members over large rotations (see Figure 15).

A typical set of hindering-torque data from a sample of the ExpSA wiring harness is shown in the brown curve in Figure 16. Note that the ordinate axis is hindering torque (in in-oz), and a positive value hindering torque indicates that the harness is hindering the deployment motion. Conversely, a negative value of hindering torque indicates that the wire harness is aiding deployment motion. Also note that the abscissa is labeled packaging angle, and a 0° packaging angle corresponds to the fully deployed configuration, while a 180° packaging angle corresponds to fully packaged.

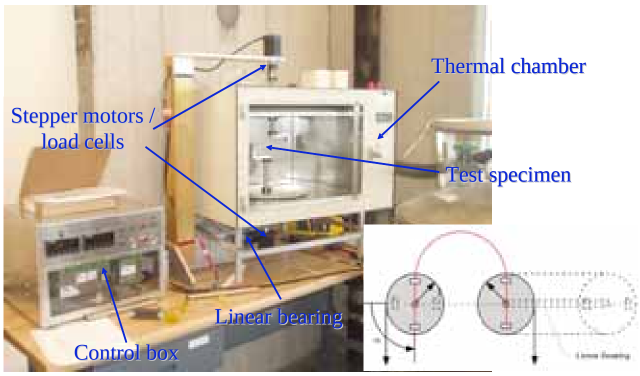

Figure 15. Torque-testing apparatus.

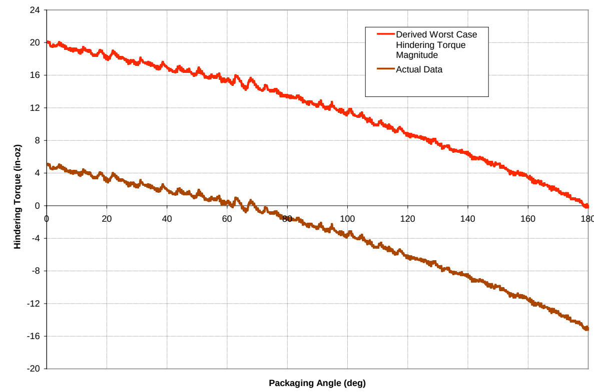

Figure 16. Typical worst-case hindering torque.

The hindering-torque data are approximately linear and the slope of the curve is equal to the bending stiffness of the wire harness. The zero-torque point on the curve can be altered due to temperature cycling of the wire insulation material or plastic deformation of the wire. Therefore in order to be most conservative, the hindering-torque results are shifted upwards (see red curve in Figure 16) such that the zero-torque point is in the fully packaged configuration, and the harness is assumed to provide a positive hindering torque, of increasing magnitude, throughout the deployment stroke.

Several different ExpSA wiring harness configurations were tested using this procedure, and the results are compared in Figure 17. Two of the configurations provided very low hindering torque (see lower two, right-hand photos in Figure 17). The first of these configurations requires the shielding to be locally removed from the three twisted wire pairs, and a small service loop to be included where the wires cross the hinge line. The hindering-torque curve for this configuration is shown in tan in Figure 17. The second wire harness configuration simply routes the wire harness diagonally across the hinge line to add length to, and lower the effective stiffness of, the harness. The hindering-torque curve for this configuration is represented by the green curve in Figure 17. Plotted in purple in Figure 17 are torque-output data measured from the pair of TEMBO® EMC hinges. Clearly, the hinges provide at least twice the necessary torque-output throughout the deployment stroke for either of the two harness installations just described. CTD provided these results to MSI for their consideration in determining the final design for the wire-harness installation.

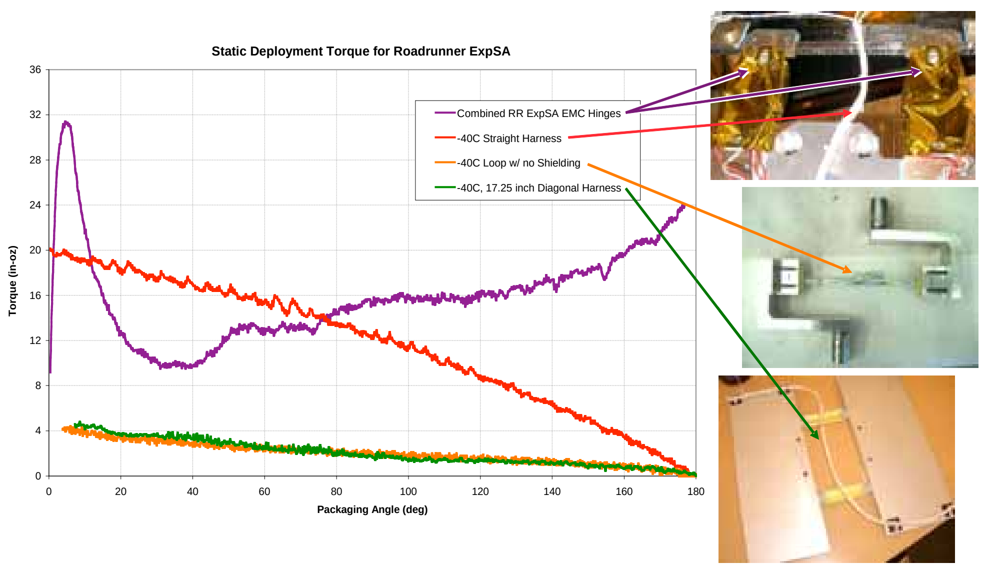

Figure 17. Torque testing data.

E. Deployed Stiffness Verification

The stiffness requirement for the ExpSA hinges was derived from a minimum deployed frequency requirement for the array of 0.5Hz. Assuming the fundamental vibration mode of the system to be bending of the hinges in response to rigid-body motion of the array, and assuming the hinges to be mounted to a rigid *ground*, the following relationship defines the approximate bending vibration frequency of the system, *f*, in Hz.

$$f = \frac{1}{2\pi l}\left(\frac{2kg}{m}\right)^{1/2} \tag{1}$$

In eq. (1), l is the length from the hinge to the array center of mass, k is the effective bending stiffness of each TEMBO® EMC hinge, m is the mass of the rigid array, and g is the gravitational conversion constant. Re-ordering eq. (1) gives the following derived bending-stiffness requirement for the pair of TEMBO® EMC hinges:

$$k \geq 2(\pi l f)^2 \frac{m}{g} \tag{2}$$

The center of mass of the array is conservatively estimated to be its geometric center, so l is defined to be 16 inches. The total mass of the array, m, is 2.2 lb_m, which requires a conversion constant of g = 386 $lb_m in/lb_f s^2$. Substituting these values, and f = 0.5Hz, into eq. (2) gives the following requirement for the hinge bending stiffness.

$$k \geq 7.2 \text{ in} \cdot \text{lb}_f/\text{rad} \tag{3}$$

To verify that the TEMBO® EMC hinge meets this requirement, the bending stiffness of the hinge was determined using finite element analysis (FEA). A quarter-model of the hinge was used with symmetry conditions and composite properties to represent each EMC laminate as shown in Figure 18. The results of the analysis are summarized in Table 1. Clearly, the hinge design provides more than adequate deployed stiffness to meet the 0.5Hz fundamental-frequency requirement for ExpSA. Indeed, the fundamental vibration mode is a flexible-body mode of the solar array, not a hinge-bending mode.[6]

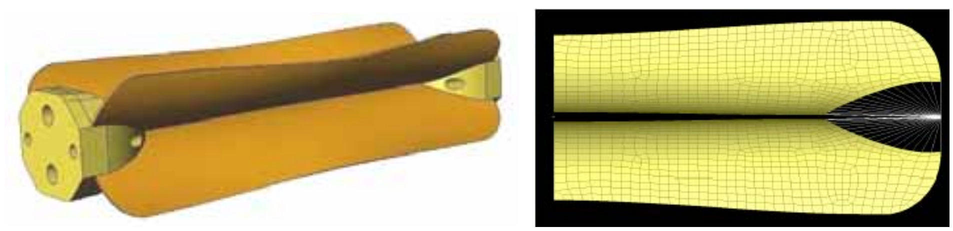

Figure 18. TEMBO® EMC hinge geometry and FEA model.

Table 1. FEA-Computed Stiffnesses for the TEMBO® EMC Hinge

Property	Value
Bending stiffness	2883 in-lb_f/rad
Extensional stiffness	1.39 E+05 psi
Torsional stiffness	27.58 in-lb_f/rad

IV. Summary

Future small spacecraft will have a need for lightweight, highly reliable, and cost-effective mechanisms for the deployment of radiators, solar arrays, and other devices. To meet this need, Composite Technology Development, Inc. has developed TEMBO® Elastic Memory Composite (EMC) materials, which accommodate very high folding strains without damage, while providing very high deployed stiffness- and strength-to-weight ratios. Over the past few years, CTD has developed and performed extensive ground testing on a TEMBO® EMC deployment hinge for radiators, solar arrays and other deployable spacecraft components. The present paper discusses the details of two flight experiments to validate the TEMBO® EMC hinge design on-orbit. The first mission is the Air Force Research Laboratory (AFRL)-sponsored Elastic Memory Composite Hinge (EMCH) experiment that will validate operation of six TEMBO® EMC hinges in the shirtsleeve, zero-g environment of the International Space Station. The second mission is the TacSat-2 Mission on which a pair of TEMBO® EMC hinges will deploy an experimental solar array.

To date, essentially all design-validation, and hardware-acceptance testing has been done on the flight hardware for both the EMCH and the TacSat-2 experiments. Only minor discrepancies have been found throughout these test campaigns, and design modifications for all but one discrepancy (EMI problem on EMCH) have been completed. In all tests, the TEMBO® EMC hinges have performed up to, or beyond, expectations. In addition, general feedback from individuals involved with the integration and testing of the hinges has been very complimentary and positive.

Key accomplishments of these tests include:

- TEMBO® EMC hinges have passed random vibration testing for the EMCH and TacSat-2 EXPA programs.
- TEMBO® EMC hinges have successfully completed deployment testing for the TacSat-2 ExpSA at room temperature and at -40° Celsius.
- Deployment-torque testing has been performed on the TEMBO® EMC hinges for the TacSat-2 ExpSA to show substantial positive design margin.
- Analysis of post-deployed stiffness of the TEMBO® EMC hinges for the TacSat-2 ExpSA show substantial positive design margin.

As of this writing, CTD was awaiting confirmation of flight manifesting for both the EMCH and the TacSat-2 payloads. EMCH is schedule to launch in late 2006 (at the earliest), and TacSat-2 is awaiting a launch-vehicle assignment for either 2007 or 2008.

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