Solid-State Hinge Mechanism for Simple Panel Deployment System

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Abstract

A common actuation method for flip-out panel deployment is a traditional torque hinge mechanism, which is successful largely due to its deterministic nature. However, these mechanisms typically require bulky support structures with high part counts. Another actuation method for flip-out deployments is a solid-state hinge mechanism, or tape spring. Tape springs have been utilized for several satellite panel deployments in the past, where the primary advantages of these systems are simple design and low part count. With the space industry on the cusp of an industrialization surge, we have identified this integrated design to provide a distinct advantage over the complex traditional systems. This paper will discuss the development process for the flight-qualified Roccor Panel Deployment System (ROC-PDS) with a specific focus on the analytical and empirical methods developed for solid-state hinge mechanism.

Figure 1: Solid-State Hinge Mechanisms and Deployment system

Introduction

The ROC-PDS was developed at Roccor, from concept to flight qualification, as an integrated solution for utilization in large constellation applications. The defining advantage of this system is that the part count is an order of magnitude less than its torque hinge competitor. As shown in Figure 3, this system is comprised of a composite tube as the primary structure, with integrated solid-state hinges. By integrating the hinges in this way, the tube can take the place of the kickoff spring, deployment torsional hinge, lockout mechanism, lockout damper, while still serving as the primary deployed structure supporting the panel.

Development of the ROC-PDS required material and structural qualification methods developed by Roccor and the High Strain Composites (HSC) community. This effort included the development of qualification techniques for high strain composites, experimental techniques for material performance measurement, testing and analysis techniques for the design and validation of subsystems like the solid-state hinges, as well as empirical and analytical methods for deployment kinematic predictions.

New Space Qualification Challenges

Roccor has successfully qualified and delivered HSC products for space-flight customers including 1) a radio-frequency precision furlable boom, and 2) a furlable antenna system; and is currently qualifying HSC products for space-flight customers including 3) an FCC-certified deorbit device, and 4) a solar array

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deployment system. Each mission’s development and qualification program followed a similar test and analysis plan to that illustrated in Figure 2. Although these four missions were relatively risk tolerant, the tasks labeled with caution symbols in Figure 2 were very costly, schedule-intensive, and performance-limiting due to a lack of industry accepted practices applying to HSCs. The lack of standards creates a roadblock for the use of HSCs for high-value DoD or NASA missions, for which a new class of high-performance deployable structures would be enabling. Roccor views collaboration with the broader space-flight community to develop industry-accepted thin-ply composite manufacturing methods, databases, engineering tools, test and qualification methods as vital to its business model.

ROC-PDS System Architecture

As shown in Figure 1, the ROC-PDS is comprised of a panel, stowage containment fixtures, a hinged boom with end brackets, kinematic mounts, a hold down release mechanism, and two solar array drive actuators. The ROC-PDS was developed at Roccor from concept to flight qualification as a low part count solution for utilization in large constellation applications. The defining advantage of this system is that, by integrating solid-state hinges into the tube, the part count is an order of magnitude less than comparable mechanized systems. By integrating the hinges in this way, the tube can take the place of the kickoff spring, deployment torsional hinge, lockout mechanism, lockout damper, and still serves as the primary deployed structure supporting the panel.
Development of Solid-State Hinge

Closed cross section tubes containing solid-state hinges have been demonstrated in the past for the use with several long antenna applications (Ref. 1). Much of the groundwork for this technology was developed by research facilities (2, 3, 4, 5, and 6) to characterize the hinge design features and performance. The intended application was to package several antennas, approximately twenty meters long, into a compact rectangular package. The deployment of this tube was mostly dependent on hinge torque, as there was little to no mass or rotational inertia at the tip relative to a system such as the Roccor PDS. Utilizing a similar tube and hinge architecture to package the Roccor PDS system would require an evaluation of hinge torque required to deploy a massive panel, as well as its ability to stabilize the panel mass once deployed. To assess the feasibility of the hinged boom for this application the deployed system was modeled in ABAQUS (Figure 4).

Results of this study showed that the first fundamental frequency mode was rotation about the boom, which cause the hinge tapes to shear relative to one another. Therefore, the two driving design requirements for the hinge in the Roccor PDS were deployment torque and shear stability. Optimization and validation of the hinge to provide enough deployment torque and torsional stiffness was the primary challenge for Roccor in the development of the panel deployment system.
Hinge Geometry and Design

The geometry of the hinge cutout in the foldable tube system was derived to both maximize torque output and reduce the high stress concentration areas that result from complex curvatures near the fold. By creating a narrow slit in the boom, the cross section effectively becomes two tape springs, which are commonly used in deployable structures for solar array applications. At the ends of the slit, however, the transition area must accommodate deformations to go from flattened tape springs to a full tube cross section. To avoid large strain areas due to the complexity of this transition area, a circular cutout was introduced. This cutout simply removes this difficult transition area.

In the hinge cutout, there are several dimensions and material properties that affect the overall performance. These dimensions include the hinge length “L”, slot width “w”, end cutout diameter “d”, tube diameter “D”. The material properties of thickness, density, and modulus (viscoelastic and elastic contributions) must be accounted for to fully characterize hinge performance.

Verification of Solid-State Hinge

Design of the solid-state hinge for the ROC-PDS required verification testing and analysis of material allowable limits, hinge torque output, and torsional stiffness. For this, several testing methods had to be developed by Roccor to investigate the properties and effects of interest such as; material bending limits, hinge performance, and performance degradation due to long term holds.

Material Testing for Thin laminate Bending

As detailed in reference 7 the column bend test was developed to combine the attributes of both the platen (Ref. 8) and LD-FPBT (Ref. 9) into a simple test method intended to measure the moment-curvature relationship of a given HSC laminate. Testing is done by fixing a laminate sample into two identical “arms” that are then pinned into clevis mounts attached to a load frame. When the load frame compresses the fixture, the arms rotate about the pins requiring the sample to curve between the two arms. Using geometry, the moment-curvature relationships can be found using methods and equations detailed in Ref. 7.

From this testing we can obtain the allowable bending curvatures, and relative strains, for a given laminate. For the ROC-PDS the laminate architecture selected contained a combination of Astroquartz and carbon fibers cured in a thermoset epoxy resin matrix. Testing was conducted on coupons cut at four orientations (0°, 45°, 90°, and 135°), and testing was conducted to obtain both the quasi-static load failure as well as the long-term hold failure curvatures (Figure 7).

Results from ultimate testing were plotted on a polar chart for visualization of “allowable failure”. The average failure of each laminate orientation is utilized to create a polar curve fit “allowable failure” value to be used in analytical failure investigations of the stowed and deploying boom structure. Results from
relaxation testing were used to develop a custom viscoelastic relaxation curve using the Prony series method.

Figure 6: Column Bend Test Fixture Geometry [10,11]

Figure 7: Material Testing of composite hinge material.

Figure 8: (Left) Curvature allowable values; (Right) Laminate Prony series output
Where the curve fit to the equations is found using Equation 1 with allowable values shown in Table 1.

\[ K^f_{\theta} = K^f_0 \cos(\theta)^2 + K^f_{90}\cos(\theta)^2 + \left[ 4K^f_{45}\cos(\theta)^2 \right] \sin(\theta) \cos(\theta)^2 \] (1)

<table>
<thead>
<tr>
<th>Orientation (degrees)</th>
<th>Curvature (rad/m)</th>
<th>Curvature (rad/m)</th>
<th>Curvature (rad/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>329.70*</td>
<td>0.73</td>
<td>N/A</td>
</tr>
<tr>
<td>90</td>
<td>328.82*</td>
<td>0.01</td>
<td>N/A</td>
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<td>275.2</td>
<td>8.03</td>
<td>13.54</td>
</tr>
<tr>
<td>45</td>
<td>306.44</td>
<td>15.13</td>
<td>25.5</td>
</tr>
</tbody>
</table>

*Maximum curvature observed due to column bend test fixture limitations. No physical failure observed.

Hinge Element Failure Evaluation

The folded boom structure was evaluated for failure simply by taking the element level curvature values and converting them into the principal values of \( K_1 \), \( K_2 \), and \( \theta \) using Moore’s Law equations (equation 2-4). For this effort, the principal curvature values were taken and re-plotted on the undeformed structure to more clearly illustrate the critical elements within the structure (Figure 9).

\[ K_1 = \frac{K_1 + K_2}{2} + \sqrt{\left(\frac{K_2 - K_1}{2}\right)^2 + \left(\frac{K_2}{2}\right)^2} \] (2)

\[ K_2 = \frac{K_1 + K_2}{2} - \sqrt{\left(\frac{K_2 - K_1}{2}\right)^2 + \left(\frac{K_2}{2}\right)^2} \] (3)

\[ \theta = 0.5 \times \arctan\left(\frac{K_3}{K_1 - K_2}\right) \] (4)

Figure 9: Converting local element curvatures to principal values using Moore’s Law conversion equations.

Hinge geometry for the ROC-PDS was initially selected to satisfy failure criteria. However, it was soon discovered that the driving design requirements would drive the hinge design. All hinge geometry trade study values were subsequently based upon the critical limits of the material testing.
Hinge Torsional Stiffness Trade Study

Torsional stability of the hinge was shown to be a driving design factor of the ROC-PDS. To address what design parameters would affect the torsional stability of the hinge most a model was developed. The model that was used to evaluate the hinges torsional stiffness was conducted using ABAQUS explicit dynamic solver, where the hinge section was fixed in all directions at one end and a pure moment was applied at the tip of the boom about the tube axis (Figure 10).

Figure 10: Torsional Stiffness trade study model setup

It was expected that the diameter of the end circle cutout controlled by the “d” variable shown in Figure 5 would be the primary driver of torsional stability due to it producing the smallest effective torsional cross section. This evaluation was conducted to evaluate the effects of both length and diametric cutout of the end cutouts. The curvature results were also compared to the material allowable values were then evaluated using the methods described earlier.

Figure 11: Initial torsional stiffness evaluation based on hinge geometry and material allowable prediction

Results of this investigation showed both that the risk of material failure due to torsional inputs was very low, and that the primary concern was geometric buckling behaviors. However, these buckling behaviors occur at least an order of magnitude beyond any operational load cases, so this risk was retired. The design output from this investigation was that minimizing the end cutout geometry and using a short slot cutout length result in the stiffest hinge geometry.

Hinge Torque Output Trade Study

Based on standard practice at Roccor with deployable structures, it is required that any deployment hinge provide enough torque to deploy the system, from any static position within the deployment, with a factor
of safety of two. The analysis model from the torsional stiffness investigation was utilized again for the torque output investigation, with the application of tip load changed and a small perturbation force added on the compressed hinge tape to promote a controlled buckling of the hinge (Figure 12).

![Figure 12: Hinge torque trade study model setup](image)

To maximize the torque output of the hinge the “w” term from Figure 5 was minimized in order to maximize the potential energy of the hinge. Verification of this design consisted of first evaluating the material survivability by modeling the folded hinge with finite elements and using the evaluation methods described earlier.

![Figure 13: Initial torque output capabilities based on hinge geometry and material allowable prediction](image)

Results of the analytical hinge studies were to select hinges with minimalized “d” and “L” terms for the hinge, however further investigations using a longer boom which allowed for more continuous deformation of the tube cross section resulted in the hinge getting deformed far passed its material allowable limits. The reason this was not seen in the initial investigation was due to the end conditions creating a rigid circle relatively close to the hinge cutout area, resulting in artificially positive margins for the area around the circular cutout. To address this issue the hinges were re-evaluated using a longer tube section (Figure 14). This allowed for more natural curvature regions to form around the hinges.
This effect was exacerbated by the ability for the full ROC-PDS system to seat itself into a system low energy state (Figure 15), where the local curvatures around the hinge often resulted in negative margin. Analysis results did not conclude with a geometric result which closed for this case, however a design alteration to the overall system was devised to add rigidity to the local area and hold the hinge open. This design feature is known as a “power band” and is the topic of another study paper currently in progress at Roccor.

Figure 15: (Left) High curvatures in full system analysis; (Right) hinge shift into low energy state.

Hinge Torque and Long-term Storage Testing
Full-scale hinged boom testing was used to validate the analysis results and determine the properties of the hinges where analytical techniques were unable to predict the behavior of this complex system. The primary test used was hinge torque testing under ambient temperatures and operational temperature extremes. This was coupled with long-term storage testing to evaluate material survivability and viscoelastic effects on strain energy relaxation.

A torque test fixture was developed and qualified to accurately measure the hinge output torque. This fixture is shown in Figure 16; the fixture uses torque cells to measure the output torque of each hinge as the boom is slowly allowed to deploy, resulting in a semi-static torque measurement. This fixture was qualified and validated by measuring the torque output of an easily modelled metallic leaf spring.
The primary resistive torque in this design was due to a flat, flexible electrical harness inside the boom. The behavior of this harness depends intimately on the boundary conditions supplied by the boom, so testing of the harness alone proved impossible. Instead, the hinge torque was measured with and without the harness, and the harness torque was derived by comparing these two torque curves. These values were then used to derive and show deployment torque margin. A typical torque curve derived from this testing is shown below in Figure 17.
Later tests at operational temperature extremes were enabled by constructing a thermal chamber around the torque test hardware. This testing was both used to directly verify the torque margin and validate the analytical predictions.

The impacts of the viscoelasticity on the deployment kinematics were also a key risk, and due to a lack of standardized test methods and stress relaxation failure models these impacts are very difficult to analytically model. Long-term storage testing was therefore used to simulate the impact of storage before deployment. Full-length booms were stowed in the anticipated storage shape, as shown in Figure 18, and the time-temperature superposition relationship was used to reduce the storage time required from years to days.

During and after storage the boom was inspected for damage. The corners of each hinge were at particular risk of stress rupture during long-term storage, so these areas were subjected to extra scrutiny. Detailed images of these areas are shown in Figure 19. After storage at elevated temperature the kick-off force, hinge torque, and final boom geometry was measured. These measured values were fed into the analytical model to better predict the deployment of the hinged boom after storage.
The results of this testing were then used to validate the analytical model, show compliance with requirements, and provide knock-down factors for post-storage deployments. In particular, the requirements for long-term storage survival and deployment torque margins were verified directly through test.

**Final Boom Laminate Architecture Features**

At the culmination of the development program, there were several design features resulting from detailed analysis and testing efforts done at Roccor. First, the hinges were strengthened by “power bands” in order to keep the slit from collapsing when the system is required to be compressed beyond the material limits of the hinge deformation. Next, the “razor backs” were added which are localized areas with adjusted thickness used to tune the required torque output of the hinge tapes to develop the required strain energy balance for the deployment. Last, the “lateral lines”\(^2\) were added in the boom, which are a localized laminate change which is utilized to tune the kickoff energy of the system. All these features were developed using the methods described in the previous section for material allowable calculations, as well as physical testing for validation of concepts and verification against flight qualification environments.
Conclusions and Lessons Learned

The primary lesson learned from this mission goes back to the age old saying of “test early and test often”. Much of the issues in this program stemmed from not doing enough validation testing up front to develop a better understanding of early concepts. A notable lesson from testing early however is that care should be taken to understand the applicable boundary conditions of the system. Early trade studies using both analysis and testing should be carried out with an effort to emulate the final system boundary conditions. Early effort test booms in this program experienced several stress ruptures; these were eliminated by including the long-term storage test in the development and qualification test flows. In addition, early hinge torque tests did not include the boom end fittings or even full-length booms. It was found that the parts of the boom outside the hinge regions, especially the proximal end fitting, change the boundary conditions of the hinge significantly and therefore increased the hinge output torque. Without this increased torque the hinges would not have met the torque margin requirements, but the increased torque with the end fitting overcame the resistive torque from the electrical harness.

Additional critical lessons learned in this program were based on the lack of accepted qualification methods for high strain composite materials. At the start of this program, it was identified that the allowable material properties based on existing standards would not be enough for characterizing the relevant performance properties for thin flexible composite structures. To qualify these structures in a relevant manor the simple methods described in this paper were devised to satisfy the needs of a high value new space customer.

References
