Ultra light self-motorized mechanism for deployment of light weight reflector antennas and appendages

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ABSTRACT

A mechanism to deploy satellite appendages such as reflector antennas or masts was developed providing a rotation angle of up to 90 degrees without auxiliary motorization. The necessary energy is stored within curved tape springs which are buckled and folded into stowed position. The deployment is triggered by release at the hold down points of the deployable appendage. New characteristics with respect to similar mechanisms are a complete guidance without friction pairs combined with a high pointing stability achieved without additional latching elements. Although other elastic collapsible hinges (ECH) exist this design is an improvement with respect to pointing accuracy, guidance during deployment and deployment torque.
The presented elastic collapsible hinge integrates several functions (deployment motorization, guidance, latching and confidence of pointing stability) in a low mass reliable design. This paper reports the development process from concept to finished product including material characterization, simulation, verification approach and lessons learned.

1. DEVELOPMENT LOGIC

The development started with a survey covering deployable mechanisms of the last 40 years. The following steps were the trade-off on materials and geometry, simulations, and functional testing.
Verification of the mechanism performance are done using an antenna dummy in a qualification process which includes multiple deployments test after a launch vibration test as well as after thermal cycling in order to gauge repeatability of deployment kinematics and reliability of end position.

2. STARTING POINT EXPERIENCES

The development of a fully elastic self motorized hinge is based on the knowledge derived studies which investigated the behaviour of resilient tape spring elements. Fundamental coherences between design and performance of such spring elements were studied by Pellegrino and Seffen at University of Cambridge, Department of Engineering, [1] [2], among others.

Two of the outstanding properties of these curved tape spring elements are a stable straight position with a high locking moment and the absence of friction during rotation. A typical example of this design is the Maeva hinge (see Fig. 1) [3] which is being redesigned to overcome existing limitations in terms of stiffness, deployment path control and deployment torque.

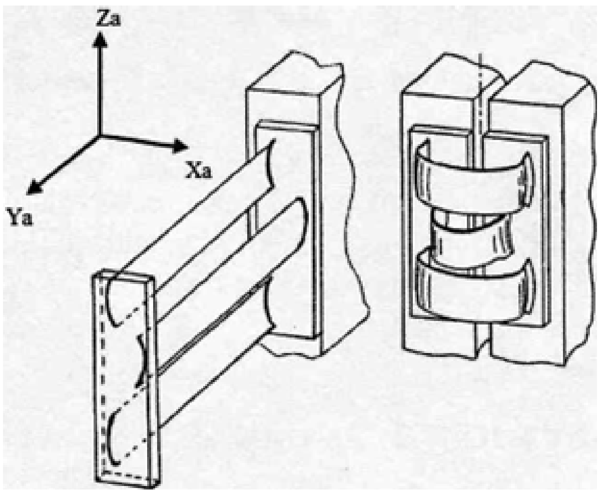

Figure 1. Maeva hinge

3. REQUIREMENTS

In order to guide the development of the hinge a performance specification was written in close cooperation with manufacturers of lightweight antennas, in particular Astrium in Toulouse.

The mechanism is validated for deployable items with inertia of maximum 60 kgm² with respect to the rotation

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axis. The weight is below 0.5 kg including interface plates to the spacecraft and the deployable item. The occupied volume in the folded configuration is 140 x 200 x 80 mm^3.

The specification foresees a qualification temperature range for the hinge of -90°C to +90°C (non-operational) and -40°C to +70°C (operational). Deployment repeatability is better than 0.005° half cone, the position accuracy at end of life is better than 0.01° half cone considering all possible effects. Stiffness of the deployed appendage is better than 2 Hz and the materials allow a storage period of five years in the folded configuration without loss of deployment torque or creeping of the resin.

4. MAIN DESIGN FEATURES

The basic design solves the challenge of building a high deformable hinge with sufficient deployment torque and end stiffness by applying spring elements of different length (see Fig. 2).

Spring length is identified as the mayor stiffness driver with the shorter spring contributing a large part of the end of deployment stiffness. The shorter spring can be seen as a kind of pivot for the mechanism. The benefit of using tape springs and not a common pin-clevis joint is the absence of friction.

The longer spring is placed 80 mm away from the short one. This distance controls the bending stiffness of the deployed hinge. The longer spring is able to be bent in an S-shape, that means it is bent in both forward and opposite directions and it can be accommodated below the shorter one which results in a high compactness of the folded hinge (see Fig. 3).

One major criterion for a weighted evaluation is the specific spring stiffness which results when accounting for the elastic stiffness of a material and its mass:

$$C_x \sim E \cdot \varepsilon_{0.2}^3 \qquad (1)$$

A trade-off including metallic and fibre reinforced materials restricted the search to stiff materials with a high elastic deformation ability.

Figure 2. Demonstration model (deployed)

Figure 3. Demonstration model (folded)

A second concern arises from the requirement of achieving a high pointing stability over a long range of temperatures. In this case the ratio of coefficient of thermal expansion to thermal conductivity is the controlling factor.

The decision to use carbon fibre reinforced plastic (CFRP) material is reached by the higher thermal stability consideration. Under assumed worst case temperature distribution the deflection can only be minimized using low CTE materials.

The more detailed analysis in the field of CFRP led to the final material selection of a pre-preg material consisting of a medium modulus, high tensile strength fibres and cyanate ester resin. An intermediate fibre is preferable for this application due to its high allowable strain. For the resin the criteria for the selection is driven by creep resistance, low hygroscopic pick-up and low coefficient of thermal expansion.

The design of the hinge incorporates four pairs (one short and one long) of tape springs in a row, each with the curvature facing inwards (see Fig. 4). This rectangular arrangement maximizes torsional stiffness.

The different length of the spring elements is compensated with four support bodies also made of CFRP. The support components provide a large cut-out with sufficient clearance to the flattened long tape spring in its bent position.

CFRP tape springs are connected to metallic fittings by adhesive bonding and an additionally screw connection. The double joining technique serves a purpose: the bond minimizes loads at the edge of the bolting hole while the bolt reduces peeling loads on the adhesive. The washer matches the curvature of the surface.

On the backside of the small spring an end stop limits its travel after passing the straight configuration (back buckling). It does not have effect on the alignment precision of the hinge because there is a gap between it and the upper part of the hinge (Fig. 4).

The necessity of the end-stop became obvious after first deployment tests with inertia dummies. Without it the instability point of the small springs was exceeded and the resulting back buckling damaged the short springs.

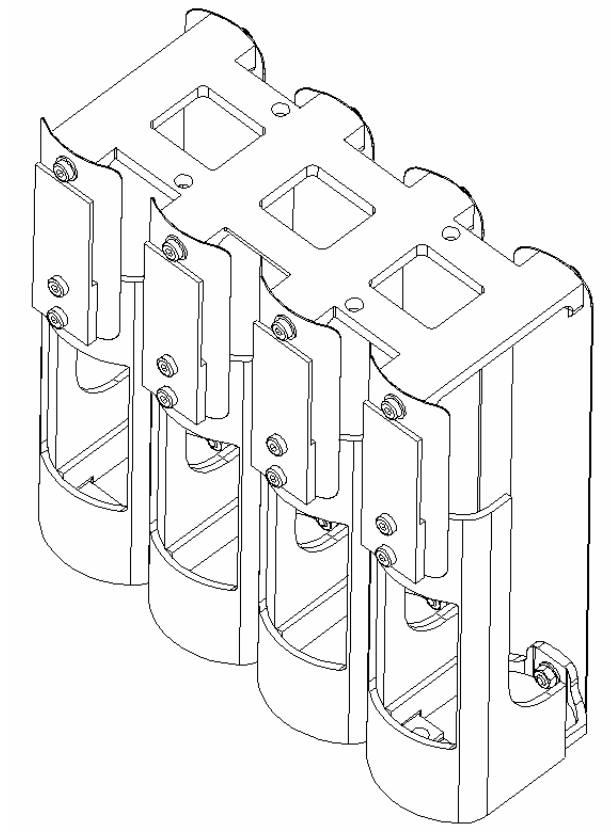

Figure 4. Deployment mechanism overview

The performance of the hinge in terms of stiffness, torque and the general ability to bend is determined by the design of the CFRP spring elements. The total thickness has to be in the range of approximately 0.3 to 0.45 mm. This allows bending in small radii within the material strain limits. A small bending radius reduces the overall volume of the hinge.

With the selected pre-preg material and a ply thickness of 0.11mm it was possible to investigate laminates up to four layers thick. Thinner pre-pregs would increase design freedom and result in more balanced laminates.

A multitude of different lay-ups was investigated using simulation software. Laminates with ply angles close to the main bending directions (longitudinal folding, transverse flattening) were selected due to their performance in terms of deployment torque and deployed stiffness. In practice they turned out to have major disadvantages. Sharp kinks at the edges occurred during folding. The $[90,0]_2$ laminate showed only poor ability to build up the S-shape and cracked during folding.

In the end only laminates with a good balance between bending and shear stiffness like [90, +45,-45, 0] proved to be resilient enough for the application.

5. SIMULATIONS

Different simulations were performed in parallel to design and test activities to predict the behaviour and correlate measurements. The fields of simulation were:

- Bending / deployment moment
- Strain and stress analysis
- Stiffness / Eigen frequency
- Thermal distortions
- Deployment process

A single tape spring FE-model was used for variation and improvement of fixation boundary conditions and spring element length in non-linear calculations (see Fig. 5).

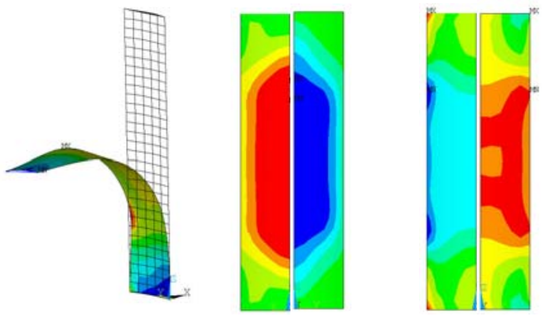

Figure 5. Strain calculation

A simplified model representing 1/8 of the designed short and long spring arrangement delivered the moment angle relation and allowed to identify the highest loaded areas during the folding and deployment. The reduced model is possible due to the symmetry of the springs.

This simulation was primarily performed with isotropic material to investigate the strain distribution. The strain in the isotropic material was than mapped onto an anisotropic tape spring with the same deflection to assess the strain within the different layers. The use of anisotropic material would have made the model numerically unstable and showed difficulties during trial runs.

Several simulation methods were used:

- Explicit finite differences for high rate nonlinearities
- Implicit finite element to gauge stress levels
- Multi-body kinematics to predict deployment of the appendages

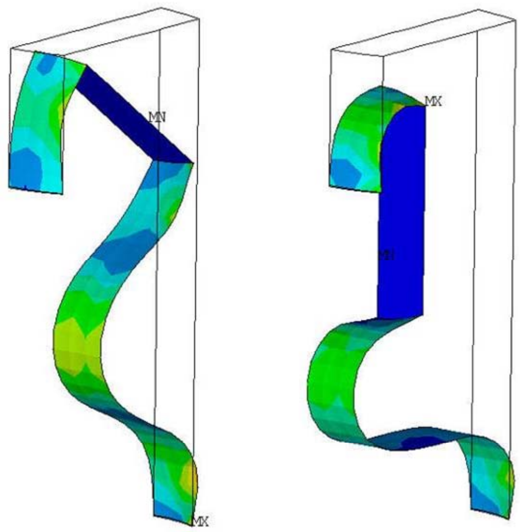

Figure 6. Folding simulation

The multi-body kinematics model (see Fig. 7) to predict the deployment of the appendage showed the same movement of the springs during deployment as the prototype in reality. But the model had to be scaled up to overcome the problem of computer accuracy with the real size model caused by the combination of small dimensions with the high loads. The complete model consisted of a pair of springs and an attached dummy antenna (Fig. 8). The number of rigid bodies had to be kept small to keep computing time acceptable.

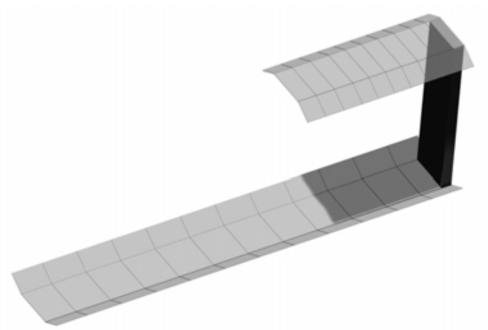

Figure 7. Multi-body kinematics model, deployed

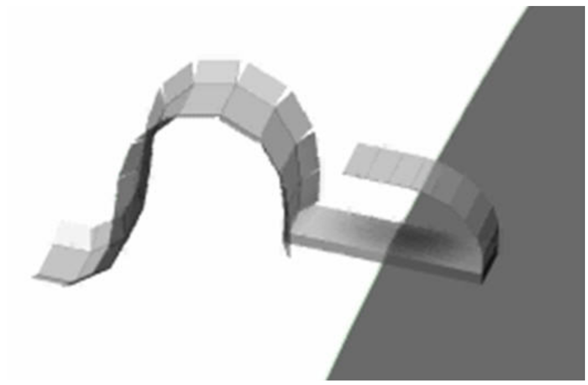

Figure 8. Model with dummy antenna, folded

For stiffness and thermal deflection analysis a complete model of the hinge was built.

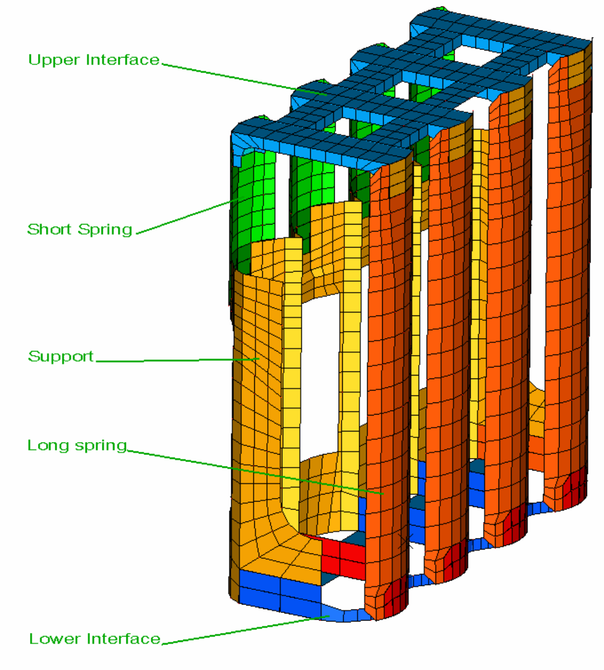

Figure 9. FE-Model for stiffness and thermal simulation

6. TESTING

6.1 Materials

The material testing was performed in order to get the real values and to rerun the analysis with them.

The tests of the CFRP material covered amongst others the following properties:

- Density
- Glass transition temperature
- Thickness
- Fibre, matrix and void fraction
- Young's modulus, maximum strain and ultimate stress in tension and compression at reference temperature, minimum and maximum temperature.
- Coefficient of thermal expansion (CTE)
- Long term stress relaxation
- Moisture pick-up
- Thermal conductivity

The tests were performed in the two orthotropic directions

The density was measured to obtain the exact mass of the model in the simulation.
The glass transition temperature of the matrix gives the limit for the maximum usable temperature of the hinge. As the glass temperature of the cyanate ester resin is much higher than needed the material fully complies with the requirements.
As mentioned the bending radius depends on the thickness. Furthermore the thickness allows assessing the manufacturing quality.
Fibre, matrix and void fraction reveal a lot about the manufacturing quality but are not really necessary for the analysis because also strain/stress tests were performed.
Obviously real values of strain, stress, and Young's modulus are important to perform a reliable and realistic simulation of the hinge.
CTE tests are very important as one of the most stringent requirements refer to pointing stability which is driven mostly by the thermal characteristics of the material.
Long term stress relaxation will be performed in order to assess the change of deployment torque over time due to storage of the hinge in folded configuration for a long period of time.

6.2 Hinge

Basic investigations in terms of CFRP bendability, component interference and handling were conducted with a test gadget (Fig. 10) representing the dimensions of the designed arrangement. This enabled an early identification of problematic issues and gave a first impression of the capability of such a hinge system.

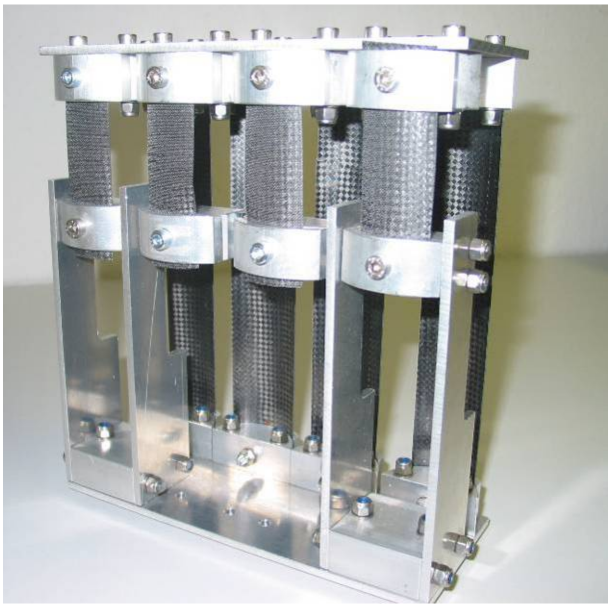

Figure 10. ECH Prototype

With the test gadget several deployments where performed with an inertia dummy to observe the unbuckling and latching of the springs. The gadget made exchanging the tape springs very easy. Different lay-ups were tested and qualitatively analyzed regarding their robustness against defects. Fig. 11 shows a side view of the prototype and the dummy in stowed configuration.

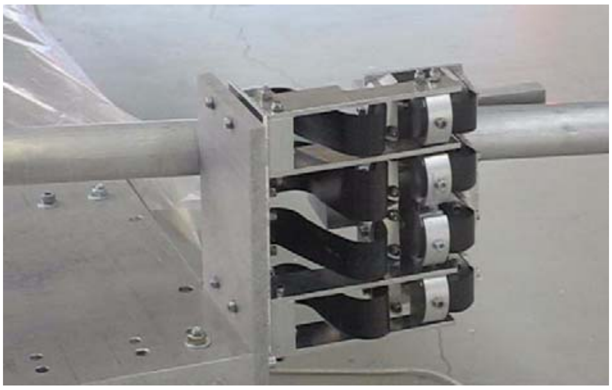

Figure 11. ECH and inertia dummy, side view

The picture in Fig. 12 shows a top view of the ECH and the inertia dummy and was taken during deployment.

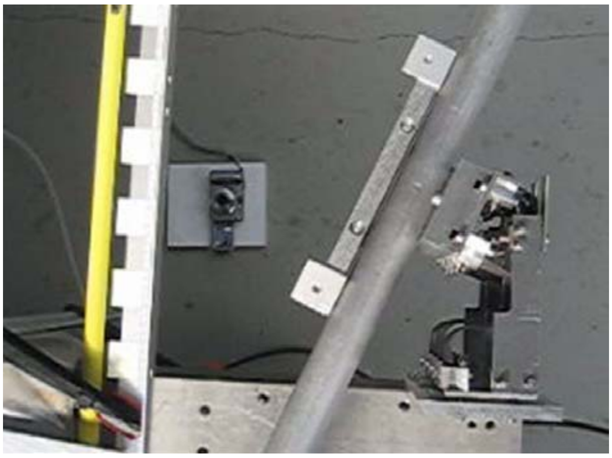

Figure 12. ECH and inertia dummy, top view

7. SUMMARY

The design shows some very promising features. It is very compact versatile and light weight, and fulfils the requirements.

Because of some delays the schedule couldn't be kept and some results were not available at publication time but will be presented during the symposium.

8. LESSONS LEARNED

Nonlinearities still cause a lot of problems and the simulation model has to be analyzed carefully. The simplification to the isotropic material is good approach regarding simplification and numerical robustness of the model but obviously doesn't reflect the real design. Without a breadboard model it's nearly impossible to assess the usefulness of the simulation as it looks good qualitatively but quantitative values are missing.

Another key issue was the thickness and the lay-up of the laminate. The bending radius depends on the one hand from the thickness and on the other hand from the lay-up. It is very difficult to control the thickness during manufacturing. Furthermore the blade can not be reworked as it is made of pre-pregs. The lay-up controls the bending radius and bending ability even more. A laminate lay-up might show good performance in theory or simulation but it fails in reality due to cracks and flaws at the edges, as mentioned for the $[0°, 90°]_2$ lay-up.

9. REFERENCES

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3. Sicre[1], Givois[2], Emerit[2], *Application of "Maeva" Hinge to Myriade Microsatellites Deployments Needs*, CNES[1], Metravib[2]