Analysis of Steel Tape-Spring Hinges for Solar Arrays Implementation in Satellites

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Deployable structures made from ultra-thin materials can be folded elastically and are able to self-deploy by releasing the stored strain energy. They are becoming more widespread because of their lower mass-to-deployed-stiffness ratio, good packaging properties and lower cost due to a smaller number of component parts and ease of manufacture [1].

So our team has researched the possible implementation of steel tape-spring hinges in solar arrays of satellites. The research has been divided into four main parts: analysis of the stored energy with simulations, analysis of the stored energy through experiments, study of the deployment sequence of the solar arrays using simulations and study of the sequence of opening of the solar array with experiments.

Analysis of stored energy with simulations

For the analysis of the tape-spring hinge it has been used the software Abaqus/Explicit. The system has been modeled as two coaxial shells with a distance between them of 10 [mm], then for the analysis only 2D finite elements has been used, since the two tapes were modeled as shells. This choice reduced the complexity of the model considerably.

The folding and deployment of the tape-spring hinge has been assumed to be quasi-static, so in order to converge the simulations it has been used the dynamic analysis on Abaqus/Explicit. As shown in figure below the model goes through three step: pinch- ing, folding and deployment. Then to check if the solution has converged, since the kinetic energy of the system to the vibrations due to the dynamic response of the system we can see in the energy history of the system through the three steps.

To converge the solution we have also added three types of damping to the system: mass scaling factor $\alpha = R$, bulk viscosity coefficient $\beta$ and the viscous pressure coefficient $\gamma$. After an analysis of the sensitivity of the system to the various damping the following values for the parameters were used for both final results:

$\alpha = 0.7$, $\beta = 0.08$ and $\gamma = 0.0002 [N/m]$. Thanks to the adding of damping parameters into the system we can see in the energy history graph, that the solution has converged, since the kinetic energy at any time is less than 1% of the internal energy and also the viscous dissipation through the three steps is very low.

In the Moment-Rotation relationship graph it can be seen that the stored torque during the folding is of 1.2 [Nm]. This result match with our expectations of the behaviour of the tape-spring hinge, where the released torque is slightly smaller of the stored torque in the folding.

A further improvements of the simulations will be the stabilisation of the system to the vibrations due to the dynamic response of the system to the imposed displacement.

Experimental set-up for individual tape-spring hinges tests

In order to correlate numerical simulations and experimental data, a set-up was built. The set-up presented in the article [1] was manual and used strain gauges. To facilitate the tests, the actual set-up was automatized and the strain gauges replaced by a load cell. A linear stage, where the tests are carried, is driven by a stepper motor. The whole is controlled by a Raspberry Pi and the user can define the length of the hinges to be tested as well as the situation to be tested (deployment or folding). Thanks to removable fixations, three different types of tape hinges can be tested.

To measure the torque available for deployment, an arm is fixed to one of the vertical cylinders. When the cylinder rotates, the arm presses on the load cell. Knowing the distance from the center of the cylinder to the load cell and the distance travelled by the cylinder, a plot of the torque as a function of distance can be generated.

Deployment sequence simulations

First of all, a feasible deployment sequence had to be identified. Considering the transportation constraints the following deployment sequence was chosen:

- **Step 1:**
  - Initial configuration
  - Schematic of the deployment sequence

MATLAB simulations were run in order to determine several aspects of the deployment. Firstly, total deployment time was determined by solving the following one-dimension ordinary differential equation (ODE):

$$\frac{d\theta}{dt} = \sqrt{M_0 + M_1 + M_2}, \quad \frac{d\theta}{dt} = \theta$$

Where $\theta$ denotes the angle between the the bus and the array, $M_0$ the array’s inertia, $n$ the number of tape-springs in the hinge (typically 2), $M_1$ and $M_2$ the stored torque inside each tape-spring, and finally $M_3$, the counteracting torque caused by drag (which is taken out of the equation in space).

The ODE applies to each array’s movement and is solved one by one considering only one degree of freedom. As the principle behind the deployment is strain energy being released in the form of kinetic energy, we had to check if the starting folding angle wasn’t going to lead to a high overshoot, causing damaging oscillations.

Deployment test

Once the deployment sequence to test was chosen, a test rig and a mechanism to hold the solar arrays had to be designed. As each solar array has dimensions 505x664 mm, a 3 m long and 1 m height test rig would make it possible to test the deployment of the five solar arrays simultaneously.

Concerning the mechanism holding the solar arrays, one major point to take into account was that it should work for different lengths of hinges connecting each panel. The way to solve this problem selected was to use linear rails. Indeed, changing the position of the carriage of the rail enables to have the correct arm length for each rotation and therefore for each hinges length.

References


[5] https://s3.sanoss.engineering.wustl.edu, 15.05.2019

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