DESIGN OF A NOVEL ECCENTRIC KINEMATIC HINGE

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ABSTRACT

Deployable space structures, such as apertures, require high precision in deployment. A novel kinematic hinge design has been developed to meet the demand for increased accuracy, targeting a repeatability of 20 microns. The design combines a tear-dropped shape eccentric pin interface, kinematic mounts, and precise force direction. The tear-dropped shape ensures contact with flat surfaces, while the eccentricity of the hinge pin allows for precise positioning. This paper presents the hinge design, test data, and future improvements. This innovative hinge design holds promise for achieving higher accuracy in deployable apertures for missions operating at higher frequencies, benefiting Earth Science mission concepts like Displaced Axis Radar (DAR), CloudCube, and multi-frequency radiometers.

1 BACKGROUND

Deployable space structures are often used to increase the surface area of a system after launch. Deployable structures most commonly include solar arrays, booms, and apertures. One unique aspect of apertures is that there is generally a desire to deploy them with extremely high precision. The required root mean squared (RMS) surface area precision is the wavelength divided by 10 or 20. For missions operating a 3 GHz, this would result in a 5 mm RMS required; for missions operating at 30 GHz, this would result in a 0.5 mm RMS requirement; and for missions operating at 300 GHz, this would result in a 50-micron RMS requirement. Most current deployable antennas have a frequency limit of ~40 GHz due to their ability to maintain surface accuracy. The exception is for missions like the James Webb Space Telescope, where apertures were deployed and corrected to micron levels of accuracy but at extremely high costs.

Mission concepts such as the displace axis radar (DAR) operating at 175 GHz [1], CloudCube operating at up to 240 GHz [2,3], and multi-frequency radiometers operating at frequencies up to 300 GHz [4] need increased accuracy for deployable apertures. We have developed a novel kinematic hinge to meet this need to enable deployment repeatability to 20 microns.

The current state-of-the-art for high precision hinges, like those on the SWOT (Surface Water Ocean Topography) mission, uses kinematic mount and loose hinge pins. The hinge pins provide rough accuracy during deployment but are removed from the load path when fully deployed, and all loads go through kinematic interfaces. However, this adds complexity, and additional mass, does not scale down well to small sizes, and has limitations on where the nesting forces can act (which are not commensurate with many spring-driven designs).

2 ORIGINS OF THE IDEA

The inspiration for this concept initially came when experimenting with the MarCO (Mars Cube One) and OMeRA (One Meter Reflectarray Antenna) hinges. These hinges had hinge pin holes that were reamed to a high degree of precision and precision hinge pins that went through the hinge. The OMeRA hinges further improved accuracy by adding a fine pitch set screw to precisely set the hinge pin angle. (Whereas the MarCO hinge pins were liquid-shimmed in place). While initially, it was investigated to fit kinematic mounts on the OMeRA hinge, the problem was that regardless of how the kinematic mounts were placed, only one mount ended up in the load path, and the rest of the load path went through the hinge pin. This meant that the hinge pin and hinge pin holes were sized very precisely, with tight tolerances. However, this approach reached the limit of their accuracy at Ka-band, 32 GHz, with a repeatability requirement of around 200-400 microns [5,6]. Deployment repeatability and accuracy could be improved by having an exactly constrained design.

To find a kinematic solution, there must be six non-redundant points of contact, usually provided by several kinematic mounts. More than six contact points mean the system will be over-constrained, potentially being located in different locations on each deployment, and less than six means the system will be under-constrained, which will result in a non-repeatable position [7–9].

This caused the realization if the load path wants to go through the hinge pin, why not find a way of making the hinge pin kinematic, such that there is one and only one configuration for the hinge to transfer the loads, leading to a highly repeatable kinematic interface.

3 DESIGN OF AN ECCENTRIC KINEMATIC HINGE

The system consists of a tear-dropped shape eccentric pin interface, kinematic mount, and known force direction. The tear-dropped eccentric hinge hole shape can be seen in Figure 1.

It obtains six kinematic points of contact by combining three elements:

1) Using a tear-dropped shape hole to create an eccentric interface to the pin, allowing the pin and hinge pin hole to become a kinematic contact.
2) Two angled kinematic contacts located out of the plane of the hinge pin, which sets the position for the degree of freedom which the hinge pin axis does not constrain.
3) Defining the locations where forces can act through to enable precision positioning and directing the force to act through that location.

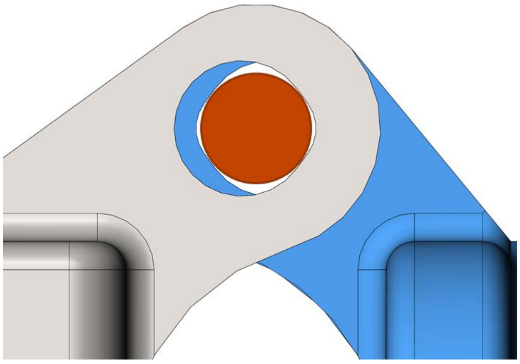

Figure 1 Close-up view of the teardrop hinge pin hole, with the hinge pin in orange.

The tear-dropped shape ensures the hinge pin contacts flat surfaces, which means that slight shifting of forces will not move the hinge pin to a new position. The eccentricity comes in terms that if the hinged joint is not preloaded, the hinge pin is free to float. However, once the hinge pin gets to the closed position and a moment is applied to close the hinge, the hinge pin contacts the flats, effectively moving the hinge pin into an eccentric position.

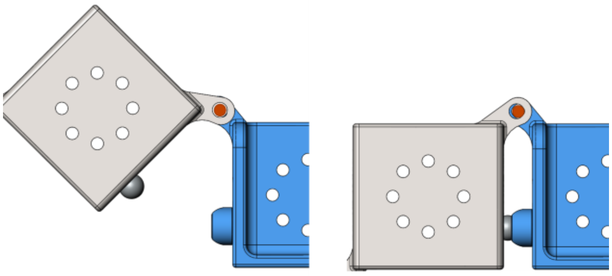

Figure 2 Hing Pin Position during deployment and after deployment.

The fact that the hinge pin is landing on flats ensures there is one and only one configuration that works between the contact points, as illustrated. If the tolerances are off (for example, the hinge pin is a bit larger in diameter), it just shifts where the contact points are on the flat but will repeatedly align to the same position. This is unlike a cylindrical surface within a cylindrical surface, where a clearance is required, which means that the hinge pin may land in a slightly different position each time.

This same approach can be accomplished by a square or diamond hinge hole, but the eccentric tear-drop shape is easier to machine.

Figure 3 illustrates the results of a method developed by Skakoon which indicates where the nesting forces which push the kinematic contacts together may act [7]. The only case where the joint will not be kinematic is if the nesting forces fall inside the triangle. In this case, the forces will cause the kinematic contacts to push away from each other, resulting in the position shifting. However, most moments if appropriately applied will have nesting forces that act outside the orange triangle. Also, unlike many traditional kinematic mounts, where the nesting forces must act in a limited window, this configuration allows a force to be applied in any direction as long as it does not intersect the triangle.

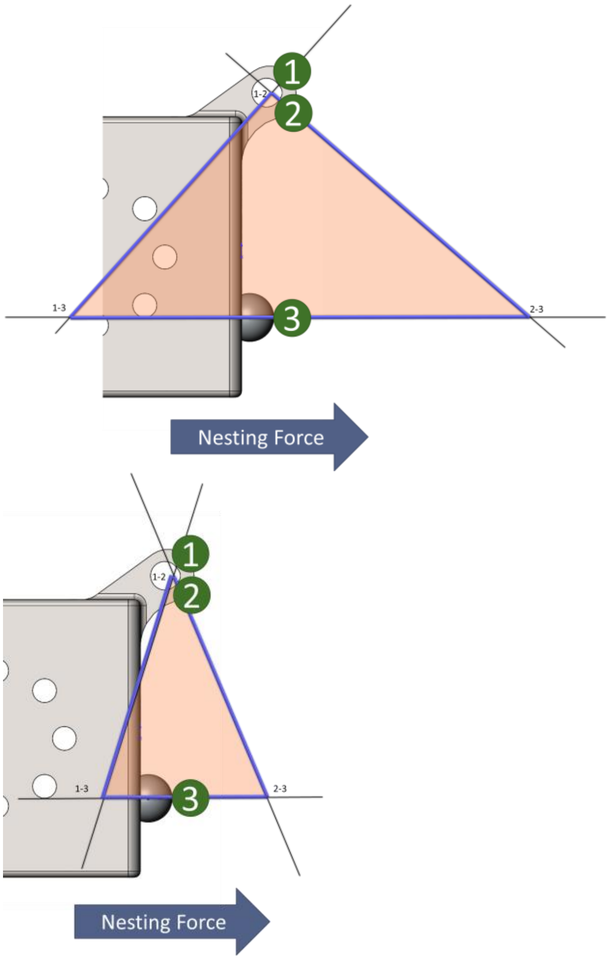

Figure 3 Regions through which nesting forces may not act

Further, by adjusting the angles of the teardrop shape and increasing the angle between the two flats from roughly 90 degrees to just under 180 degrees (a 180-degree angle would no longer be kinematic), the no-go area for forces can be dramatically reduced in size, shown in Figure 3, bottom.

4 HARDWARE CONSTRUCTION AND TESTING

To test the concept, an aluminium hinge with an eccentric tear-dropped hole was developed. A long precision steel pin was placed inside the hole, and one kinematic mount was located opposite the hinge. One side of the hinge was bolted to an optical bench, whereas the other side of the hinge was gravity offloaded to allow it to deploy.

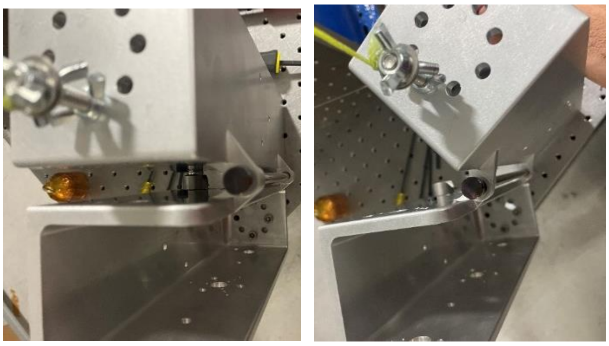

Figure 4 Test Article Stowed (Left), Partially Deployed (Right)

Two different steel hinge pins were tested. One was ¼" in diameter, and another was 15/64" in diameter. The ¼" pin was designed to contact in the centre of the flats, whereas the 15/64" pin was contacting closer to the transition zone, between the flats and the small radius in the teardrop.

To test the deployment, first, the initial position of the hinge was measured using a Faro arm to contact 3 points. Then the joint was deployed, and the same 3 points were measured again. The translation of these points, both in X, Y, and Z, and the angle of the plane was calculated to obtain a deployment error. Deployment results were plotted on positional error versus angular error of the joint. The first position has zero error, as this was the initial location all future points were measured relative to.

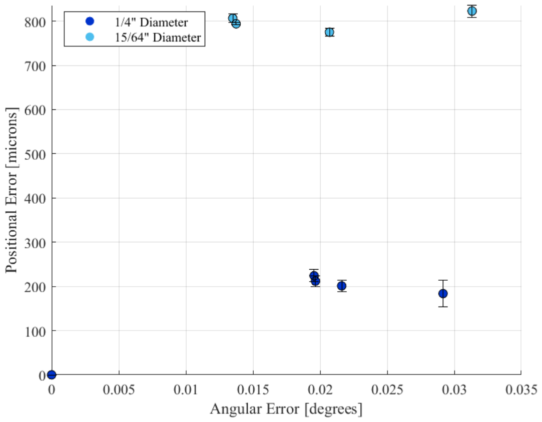

Figure 5 Hinge Deployment Error

From this plot of data, having a hinge pin that lands in the centre of the flats produces much more reliable results, with an average error of about 200 microns. In contrast, the 15/64" diameter hinge pin does not use the eccentricity to its advantage so has much worse performance. However, it did not achieve the 20-micron repeatability target, which has been observed when using three kinematic mounts instead of 1 kinematic mount and the two eccentric hinge holes.

5 FUTURE WORK

There are two key changes that can improve deployment repeatability. First, in the original design, Figure 3 simplifies the design to a 2D case, where only three points of contact are required. In the 3D case, six points of contact are required. These six points of contact come from four points of contact along the hinge pin (locations 1 and 2 in Figure 3) and two points for the sphere in a V-block (location 3 in Figure 3). However, when investigating the points of contact in the plane of the hinge and where the nesting forces must act, the nesting force is acting in the wrong region. By splitting the V-block, the region through which the nesting force acts can be expanded. Please note that the shaded region in Figure 6 indicates acceptable locations for the nesting force, unlike Figure 3.

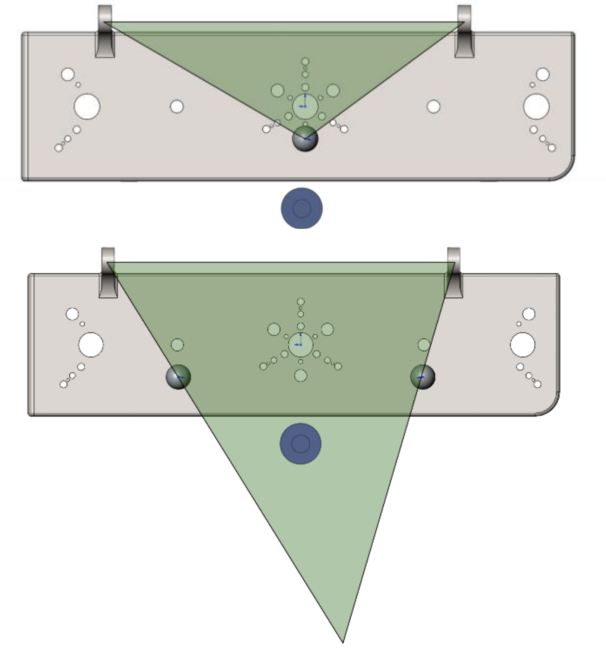

Figure 6 Acceptable nesting force location for a single V-bloc (top) vs. a split kinematic mount (bottom).

In the deployment test setup, the nesting force was not acting in the correct direction, meaning not all the constraints were properly in contact. By moving to a split block, the nesting force could act in an acceptable region. This change should improve the deployment repeatability.

A second change would be to make the hinge barrels out of a stiffer material than aluminium. This could be done by building the entire hinge body or eccentric teardrop inserts out of steel. However, this likely has a secondary effect when compared to the nesting force not acting through the right direction.

6 CONCLUSIONS AND LESSONS LEARNED

Eccentric tear-dropped-shaped hinge pin holes enable a hinge pin to become part of a kinematic system, providing four of the six required points of contact for exact constraint.

Having an exactly constrained system can lead to highly accurate deployments, enabling antennas to operate at even higher frequencies. However, care must be taken to ensure there are no redundant constraints and that all dimensions are considered, not just a simplified 2D case. While the 2D case can be helpful for initially developing constraints, it is important to account for the 3D case before building hardware, as shown here. This could have saved test time. In summary, the key lessons learned are:

1. Exact constraint, using 6 points of contact can improve deployment accuracy.
2. Ensure the location of the nesting force is correct, and ensure the next force location is checked in 3D, not just in a 2D simplification.

7 ACKNOWLEDGEMENTS

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