FOUR-BAR LINKAGE AS OPTIMIZATION OF
A SPRING DRIVEN DEPLOYMENT MECHANISM
FOR POLAR PLATFORM DRS ANTENNA MECHANISMS

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ABSTRACT

Motor torque of torsion spring driven mechanisms decreases during deployment. That effect can be
compensated and motor torque distribution can be optimized using a four-bar linkage to transmit the torque
from actuator to deployment hinge.

Selecting an adequate four-bar linkage geometry, almost the total spring motor torque can be available at the
beginning of deployment, and the motor torque at end of deployment at the hinge can be much higher than the
actuator motor torque. In that way, in the most critical moments during deployment, such as the beginning and
the end, the highest motor torque is provided. Redundant bearings can be installed on articulated bar
linkages for higher reliability.

A four-bar linkage transmission between the spring actuator and the deployment hinge has been
implemented in Polar Platform DRS Antenna Deployment Mechanism. Such a design has been successfully qualified to Polar Platform qualification levels, including functional tests, vibration tests, thermal vacuum tests, thermal cycling test, life test, etc.

Keywords: Four-bar linkage, transmission, spring motor, optimization, deployment mechanism.

1. INTRODUCTION

Polar Platform (PPF) is an earth observation platform to be used in low earth, near-polar, sun-synchronous orbit,
by a wide variety of different payloads suitable for earth observation and remote sensing of the complete Earth
surface and Earth atmosphere. PPF will provide support services and functions which are needed for
instrument operations.

The first satellite using PPF is ENVISAT, devoted mainly to earth observation. Other future users can be focussed on operational meteorology, remote sensing, etc. PPF and payloads will be monitored in real-time
with the direct to ground link (within the constraints of visibility), and with the DRS Ka band link. That DRS
Ka band antenna uses an Antenna Pointing Mechanism (APM) to point to the adequate DRS geo-stationary
satellite.

DRS Ka band Antenna and Antenna Pointing Mechanism require some additional mechanisms, such
as, launch locking devices to withstand launch loads, release mechanism to allow the starting of the
deployment, and a deployment mechanism to deploy it and perform the latching once achieved the correct orbit.

DRS Antenna Mechanisms include those elements. The deployment mechanism does not require retraction in
orbit, so, the most cost effective solution is a spring driven actuator with four torsion springs.

The total mass of APM & the 0.9 m diameter Antenna is in the order of 26 kg. Stiffness requirements (> 5 Hz
deployed and > 100 Hz stowed) make necessary a Carbon Fibre Reinforced Plastic (CFRP) tube, 126 mm
diameter and 2.5 mm thickness, and also three Antenna hold downs and one mast hold down. Once deployed,
the elevation axis of the APM is located at 2 m from the PPF structure.

One of the main drawbacks of torsion spring driven mechanisms is the fact that the provided torque
decreases along the deployment process and, although they provide the maximum motor torque at the very
beginning (one of the most critical moments in a deployment due to the static friction), the provided motor torque is significatively smaller at the end of deployment. At this moment, peaks of resistive torque
due to latching systems may be important, and can reduce drastically the available torque margin.

Another point to take into account for the selection of a torsion spring motor is the total deployment angle. Big
angles of deployment can make the necessary springs too long and too massive.

Proc. Sixth European Space Mechanisms & Tribology Symposium, Technopark, Zürich, Switzerland, 4-6 October 1995
(ESA SP-374, August 1995)

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Those two potential problems can be solved by using a transmission which supplies higher motor torque in the most critical moments of deployment (beginning and end of deployment), and which provides a good global ratio between the deployment angle and the actuator total rotation.

Besides, that transmission must not reduce the efficiency of the system, and must not induce additional significative resistive torques.

A spring driven mechanism was selected as baseline in the Polar Platform DRS Antenna Deployment Mechanism due to the fact that it fulfils the requirements and it was the most cost effective solution.

A four-bar linkage transmission between the spring actuator and the deployment hinge was found as the most adequate to be implemented.

2. DESIGN REQUIREMENTS

The most critical requirement from the mechanism performance point of view is the torque margin required for the deployment, taking into account that the margin must be maintained every time in the orbit including sun or shadow location of PPF (polar orbit provides changing thermal conditions), and that the actuator must be one failure tolerant.

The mathematical equation for the required torque (T) is:

\[ T \geq 2.0 \times (1.11I + 1.2S + 3F + 3.0Hy + 3.0Ha) \]

where every term means sources of resistive torque due to:

\[
\begin{align*}
I & \quad \text{Inertia} \\
S & \quad \text{Spring} \\
F & \quad \text{Friction} \\
Hy & \quad \text{Hysteresis} \\
Ha & \quad \text{Harness, and others}
\end{align*}
\]

Values to be included in every term of that equation (sum of sources) must be selected taking into account worst cases for that source, even in the case of potential compensation of effects.

Due to envelope requirements, the elevation of the deployment hinge respect to the interface plane was required. Nevertheless, due to stiffness requirements, the most adequate location for the actuator was as close as possible to the interface plane.

Reversibility of deployment is not required in orbit, although it is required on ground during integration and test campaign.

3. DESIGN CONCEPT

The actuator used was a spring driven motor (4 torsion springs) with a damper coupled to its main shaft. It provides a motor torque of \( \approx 84 \text{ Nm} \) at deployment start.

The hinge concept is based on two pairs of hard mounted angular contact ball bearings. The main source of resistive torque in the deployment mechanism is the harness (\( \approx 4.5 \text{ Nm} \)), composed of four bundles of high number of twisted shielded pairs of electrical lines, covered by an overall braid (additional shielding) and a tape for thermal control purposes. Nevertheless, all sources of resistive torque applicable in different instants during deployment were taken into account.

The fulfillment of the torque equation with a direct transmission would require a massive set of springs. Therefore, the selection of an adequate transmission to compensate the reduction of torque during the 101.25° of deployment seems to be logic, trying to elevate the available torque just when the resistive torque increase due to the increase of the harness resistive torque and due to the latches effect. Besides, the reduction of the rotational angle in the actuator shaft would help to reduce the number of coils of the springs, and, in that way, reduce the actuator mass.

In a first glance to the deployment system, several alternatives seems practicable for the increase of the transmitted torque:

- Four-bar linkage (quadrilateral link) transmission.
- Spur gear.
- Gear train.
- Epicyclic or planetary gear.
- Worm gear.
- Bevel gear.
- Harmonic drive gear.
- Cycloid drive gear.
- ...

Nevertheless, if the deployment system is analyzed in more detail, with the exception of the quadrilateral link, none of those alternatives seems feasible because, although they increase the torque provided by the actuator, they also increase the necessary actuator shaft rotation angle to perform the complete deployment. It means that longer springs would be required, having a very important mass impact.
Besides, those alternatives have the following disadvantages:

- They are intolerant to misalignment. Fine adjustment is usually required.
- Lubrication must be provided, and analyzed in detail.
- Contact stresses must be controlled.
- They are sensible to temperature variations.
- They usually are subject to wear.

Therefore, the only alternative that have the potentiality to adapt the transmitted torque to the resistive torque at the deployment hinge, is the quadrilateral link. Its only drawback is that the increase on torque is only provided in a limited range of its movement, and in the rest, a decrease of the available torque must be handled. So, the use of the quadrilateral link would require a detailed selection of its geometry to get the maximum transmitted torque where it is really required. That is at the start of deployment, and at the end of deployment.

A check in the intermediate area is mandatory. That characteristic of the quadrilateral link makes it to be very adequate for a spring driven mechanism because, although it can reduce the available torque when the spring provides a higher value, it can increase significantly the torque when the spring provides a lower magnitude.

A four-bar linkage between the actuator output shaft and the deployment hinge, is the more adequate transmission to minimize such problems without big complexity increase. Even, the four-bar linkage can be also used as a proper latching system if their over-centre configuration is adequately used at the end of deployment.

Nevertheless, as there are a big range of thermal conditions for deployment according to specified thermal environments (polar orbit), such a solution seems to be not adequate due to the difficulty to control the behaviour of the over-centre location and the necessary forces to achieve it. A very fine adjustment would be required, and the possibility of stiffness variation would be very difficult to control.

With the quadrilateral link transmission, no tight fit is necessary in the joints of the linked quadrilateral, because the actuator springs pre-load the transmission every time. In that way, the resistive torque due to friction in the articulations is minimum.

Such a concept has been used in Polar Platform DRS Antenna Deployment Mechanism. The used articulated quadrilateral link is provided with redundant flanged journal bearings in every articulation, and the torque transmission is performed by using a spline coupling in the actuator output.

That kind of transmission can be used, not only with spring driven, but also with motor driven deployment mechanism, for example in cases where actuator and
hinge axis are not aligned, or in cases where using a constant angular velocity actuator, a reduction of that angular velocity at end of deployment is preferred.

Several aspects must be taken into account in the design of such a transmission:

- Maximum deployment angle versus maximum actuator rotation.
- Actuator-shaft/deployment-hinge torque-ratio in function of the deployment angle.
- Hinge loads.
- Maximum torque in the cranks.
- Transversal loads induced by mechanical environment (test vibration, launch induced loads,...).
- Transmission stiffness.
- Loads on bearings and shafts located in the articulations.

A four-bar linkage is characterized by its four main dimensions. One length defining the distance between fixed joints, and the other three lengths defining two cranks and the connecting rod.

Those main dimensions must be selected to adapt the output transmitted torque, to the deployment resistive torque, taking into account the required margin and one failure tolerance in the actuator.

4. DESIGN DESCRIPTION

The quadrilateral link used in the torque transmission of DRS Antenna Deployment Mechanism was optimized achieving the following configuration:

- Distance between fixed joints : 235 mm
- Actuating crank : 172 mm
- Connecting rod : 132 mm
- Dragged crank : 141 mm

Deployment mechanism, actuator, hinge and quadrilateral link transmission can be seen in Figure 1.

The actuating crank is directly joined to the actuator shaft by a spline coupling, and the dragged crank is rigidly joined to the deployable mast in a point close to the deployment hinge.

Each of both articulations joining the connecting rod with the cranks are provided with redundant journal bearings (4) and a 8 mm diameter Titanium Alloy pin. As both articulations are pre-loaded by the actuator every time, there is not necessity a tight fit. It means that the resistive torque induced by the quadrilateral link is very small.

Figure 2 shows how the deployment angle (output) change in function of the actuator shaft angle (input).

![Figure 2. Deployment Angle (Output) vs Actuator Angle (Input).](image)

Figure 3 shows the torque ratio in function of the actuator shaft angle (input).

That design provides the minimum motor torque at the hinge in a range from 25° to 35°, and the maximum, at the most critical points of deployment, at the very beginning, and at the end of deployment.

![Figure 3. Torque Ratio vs Actuator Shaft Angle (Input).](image)
Figure 4. Comparison between Resistive Torque and Deployment Motor Torque.

Selected configuration provides a relation between total deployment angle (101.25°) and total actuator angle (67.27°) of 1.505. The torque transmission ratio is 0.9 at the starting of deployment, 0.37 at 35°, and 1.5 at the end of deployment (101.25°).

Figure 4 shows the comparison between the resistive torque (included all majorization factors) and the deployment torque, including also a failure in the actuator.

Cranks and rod of quadrilateral link are made of Titanium alloy with the following properties:

\[
\begin{align*}
\text{Area} & = 1.44 \times 10^{-4} \text{ m}^2 \\
I_{xx} & = 6.59 \times 10^{-9} \text{ m}^4 \\
I_{yy} & = 2.94 \times 10^{-9} \text{ m}^4
\end{align*}
\]

The stiffness achieved in the transmission (quadrilateral link) used in the deployment mechanism is such that it provides a first eigenfrequency above 180 Hz, and it is decoupled from the main eigenfrequency of the complete mechanism (≈ 145 Hz).

5. QUALIFICATION TESTS

Such a transmission and the complete DRS Antenna Deployment Mechanism has been successfully qualified to Polar Platform Qualification Levels. The most significative tests performed during qualification test campaign, and the corresponding levels are:

- Functional tests (several deployments)
- Sinus vibration tests: up to 15 g
- Random vibration tests: (≈ 10.45 g RMS)
  - 20 - 100 Hz: +3 dB/ct
  - 100 - 400 Hz: 0.11 g^2/Hz
  - 400 - 2000 Hz: -4 dB/ct
- Thermal vacuum operational tests
  - Low Temperature: +80°C
  - High temperature: -20°C
- Thermal cycling test:
  - 8 cycles
  - From +80°C to -45°C
- Life test

After all performed tests, the four-bar linkage transmission did not exhibit any damage or malfunction, and the repeatability of the deployment performance were maintained.

Figure 5 shows the real quadrilateral link during integration phase, and Figures 6 and 7 shows the deployment mechanism hardware as tested in the qualification test campaign of the DRS Antenna Mechanisms.

Figure 5. Quadrilateral Link.
6. CONCLUSIONS

A quadrilateral link transmission has been found to be the most adequate one, in cases were a spring driven actuator is used in deployment mechanism, mainly when actuator shaft and deployment hinge are not aligned.

Major characteristics of such a kind of transmission are the following ones:

- Selecting the adequate geometry, it adapts the available motor torque to the deployment resistive torque.
- It compensates the decrease of the deployment torque provided by a spring driven actuator along the deployment, getting a higher motor torque when it is required. For example, at end of deployment. It means that it provides an optimum distribution of torque availability during deployment.
- It requires a very simple design and low complexity.
- Its manufacturing is very simple.
- Its integration is also very easy.
- It allows a very simple coupling and de-coupling between actuator and deployment hinge during tests campaign.
- It does not requires lubrication.
- It is tolerant to misalignments between actuator shaft and deployment hinge.
- It does not require fine adjustment.
- It is not sensible to thermal distortions.
- It reduces the spring mass, making the actuator total rotation angle smaller than the deployment angle.
- It provides very good reproducibility of the deployment.
- It shows no wear.
- It is cost effective in comparison with other transmissions.

Quadrilateral link transmission can be used also in motor driven mechanism, and has a high potentiality to be used in a big variety of deployment mechanisms.

Four-bar linkage has the possibility of being adapted to a wide range of constraints and can be optimized to be adapted to the corresponding deployment hinge resistive torque.

Such a transmission has been implemented in Polar Platform DRS Antenna Deployment Mechanism, and has been successfully qualified to Polar Platform Qualification levels.

Four-bar linkage transmission is a simple, cost effective way to optimize the torque provided by a spring driven actuator.