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DESIGN OF A HIGH-TENSION ELASTICALLY DEFORMING SPACE TETHER DEPLOYER

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ABSTRACT

Several future applications for space tethers such as tethered artificial gravity, space hooks and the space elevator, feature high-tension tether deployment of fail-safe tethers.
This paper presents the design of a deployer for high-tension flat space tethers that should further strengthen the case for future high-tension space tether applications. The presented tether deployer features two sets of linearly activated pinching plates, which are elastically hinged on cross-flexures. The elastically deforming design avoids the use of bearings and gearboxes. The fixation of the (flat) tether between flat pinching plates avoids bending of the tether, which occurs in a design using friction wheels. The bending of the tether around a friction wheel lowers the allowable tension in the tether, which is avoided in the presented design.
The use of elastic hinges in space is growing, but usually the forces that occur are quite small. In the case of the presented tether deployer, the forces are extremely large, which is possible because the width of the tether is about one meter. The plate flexures are as wide as the tether, allowing very large forces. The width of the plate flexures also makes the mechanism very rigid, which is important when the force in the tether is large.
The tether deployer design presented in this paper is performed for the case of MARS-g, a low Earth orbit artificial gravity test facility. The tension in the tether can be as high as 400 kN while the resulting tether deployer mechanism weighs only about 500 kilogram for low speed deployment. The design can be adapted for high speed deployment simply by adding a more powerful motor; the tension in the tether will remain the same, only more power is required. The design is therefore easily adaptable for other uses such as space hooks or the space elevator.

1. INTRODUCTION

Space tethers can be used for many different tasks such as returning cargo and personnel from the space station [1], electrodynamic tether propulsion, tethered Artificial Gravity (AG) [2], rotating tethers for momentum transfer and the space elevator. The latter three examples require a high tension tether deployment mechanism. The design of such a mechanism will be presented in this paper. The design is done for a tethered AG satellite, MARS-g [3], but can be easily adapted for any high-tension tether application.

MARS-g is an acronym for **M**anned **A**ntecedent for **R**educed and **S**imulated **g**ravity. Illustrated in Figure 1, it is a concept for a tethered AG satellite that can serve as a test-bed for a future mission to Mars, which is on the agenda of both the ESA and the NASA. In the current design, MARS-g will be used for 14 different AG levels in 14 separate missions, which will each last half a year.

Figure 1: MARS-g

The tether of the MARS-g mission is a flat, tape shaped tether with thickness varying from 0,1 mm to 1,8 mm and a width of one meter. The flat tether accommodates a large surface to hold the tether and is failsafe.

To save on fuel, the tether for MARS-g will be extended to its full length of 2 kilometer, by means of thrusters. When the tether is deployed, a slow rotation is introduced by the thrusters, after which the tether is retrieved to increase the rotational velocity and the gravity level. This procedure saves on propellant for the MARS-g mission, but it adds the need for a high tension reeling mechanism. While the tether is being retrieved, the gravity level and thus the tension in the tether will rise, resulting in a maximum tension of 440.000 N at one gee, since the manned capsule is estimated at 40 tons (with an added factor of safety of 1,1).

With the high tension in the tether, being reeled parallel with the artificial gravity that is generated by the rotation, the system is comparable to a 40 ton elevator or crane.

2. CONCEPTUAL DESIGN

While the common concept for a crane or elevator is a winch-type design with or without several pulleys, it was quickly abandoned for the space tether deployer. It was found that the large forces involved would make the bearings needed for such a design very heavy, and the system as a whole very hard to get space qualified. The two winch-type concepts that were considered are shown in Figure 2 and Figure 3

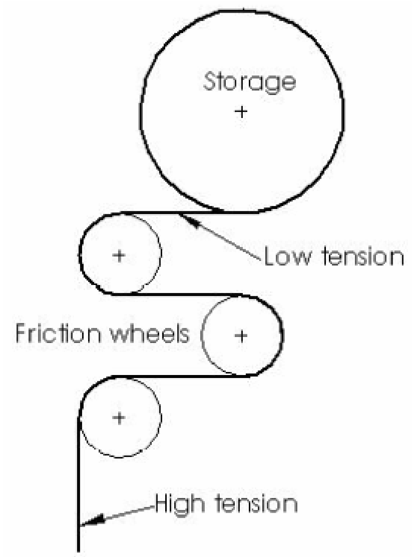

Figure 2: Many friction wheels

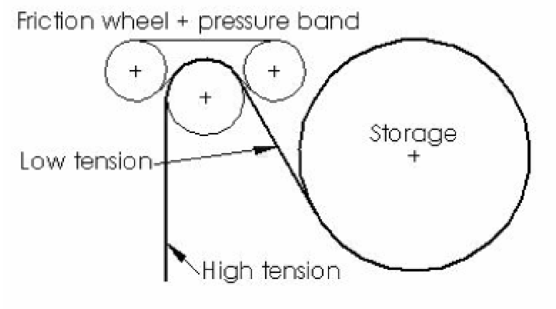

Figure 3: friction wheel + pressure band

The concept that was finally selected is based on a piezo-actuator system, used for covering large distances with extreme precision [4]. The concept for the space tether deployer is shown in Figure 4.

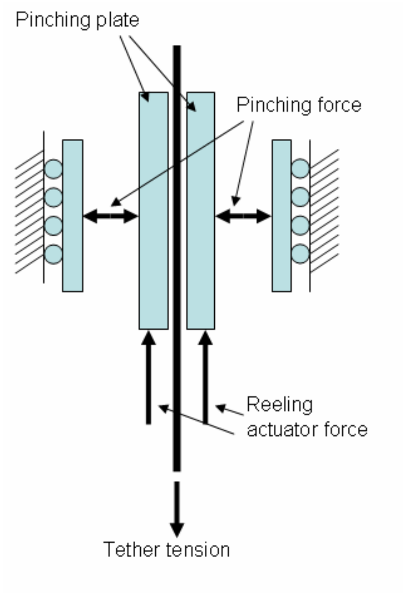

Figure 4: Pinching plates

2.1. *Self locking*

The pinching force to hold the tether in between the pinching plates is very large. For this reason it was decided to use a self locking mechanism, instead of a pinching actuator. The selflocking mechanism is illustrated in Figure 5.

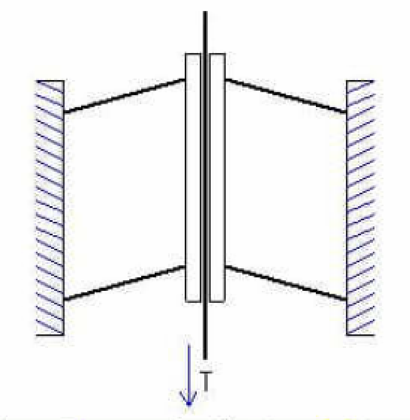

Figure 5: self-locking

In a self-locking mechanism, the tension of the tether itself will now pinch the tether, eliminating the use of a pinching actuator.
The required pinching force required depends on the friction coefficient of the tether material on the material of the flat plates. While the tether is made of dyneema, a suitable, high friction material is selected for the surface of the flat plates resulting in a (usable) friction coefficient of 0,4 [-]. With a maximum tension of 440.000 N the pinching force has to be 550 kN.
As is illustrated in figure Figure 5 the pinching force will be delivered by a self-locking mechanism. Self-locking will occur if the angle θ, in Figure 6, is small enough.

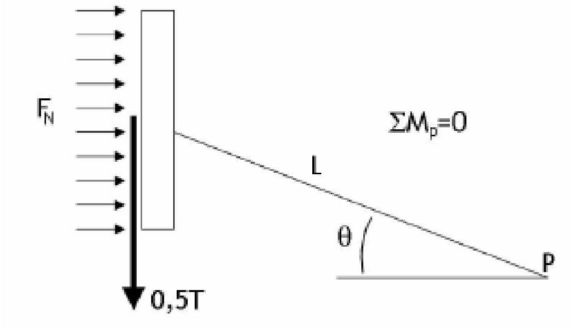

Figure 6: self-locking angle

In this case, where the friction coefficient is 0,4 the resulting maximum angle is 21,8°.

2.2. *Flexible hinges*

The motion of the pinching plates is supported by a flexible hinge, because of the small rotation required. An example of a flexible hinge is given in Figure 7.

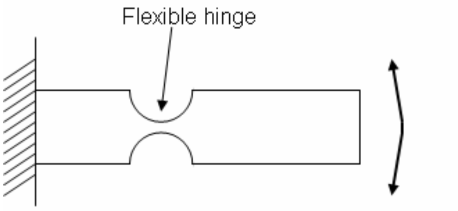

Figure 7: hole flexure

With one end of the element fixed, the other end can be rotated because of elastic deformation in the flexible hinge. Another example of a flexible hinge is a cross flexure, shown in Figure 8.

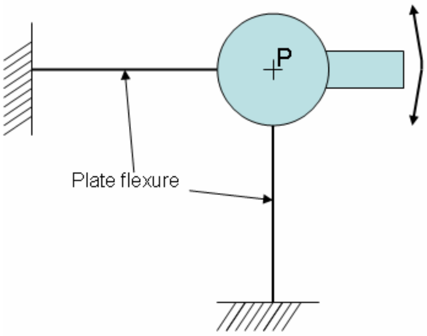

Figure 8: cross flexure

A cross flexure makes use of two plate flexures, thus creating a flexible hinge that rotates around point P in Figure 8. Cross flexures are used in the design of the tether deployer. For cross flexures it is important to know that the distance from the plate flexure to point P should be kept as small as possible. Furthermore, flexible hinges are limited to use in tension, they will buckle under pressure.

2.3. Final concept

Two sets of pinching plates are needed for the tether deployer, just as one needs two hands to retrieve a rope under tension. With two pinching plates and tether storage, the concept is shown in Figure 9.

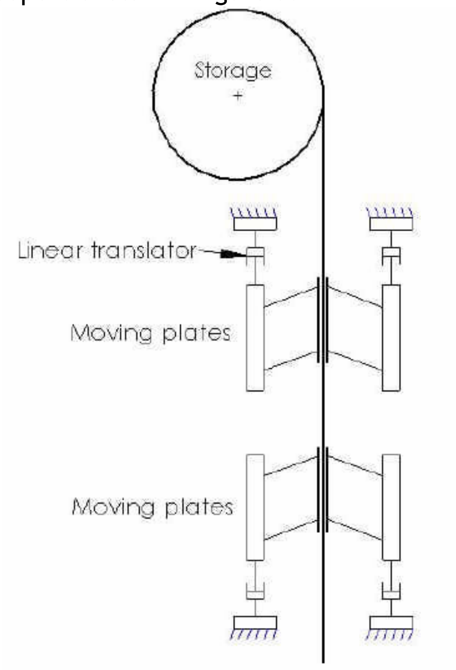

Figure 9: final concept

The linear translators can alternately push the tether to the storage drum. Above the plates that hold the tether, the tension in the tether is close to naught.

2.4. Pinching a tether

As mentioned before, the pinching plates will hold the tether by pinching it in between them. When pinching a tether, the tensile strength of the material decreases. In the case of dyneema, the tensile strength will decrease to 30% of the original value at a pinching pressure of 30 bar [5]. In the absence of more accurate information on this phenomenon, a linear dependency has been assumed. The result is illustrated in figure Figure 10. If in reality the dependence is different, the design can easily be adjusted.

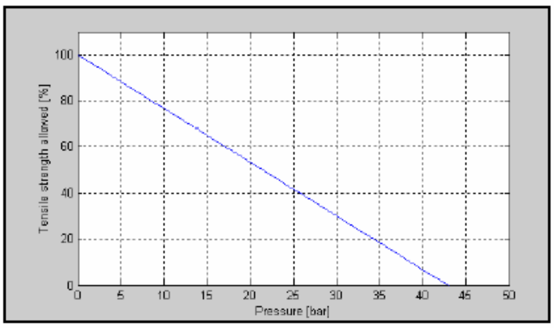

Figure 10: tensile strength vs. pressure

To compensate for the loss in tensile strength it is proposed to apply a varying pressure on the tether while pinching it in between the pinching plates. This is illustrated in Figure Figure 11. When the tension in the tether is high, at point a, the pressure should be low. At the other end of the pinching plate the tension is almost naught, so that the pressure can be high. This can be obtained by placing the point of rotation of the pinching plate, z, at the right location. It was found that for this case the point of rotation should be at around x(z) = 2/3·h of the length of the pinching plate.

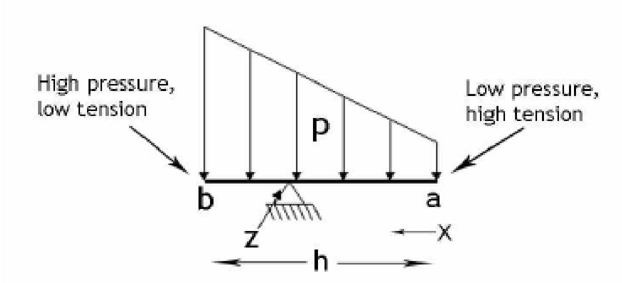

Figure 11: varying pressure

3. DETAILED DESIGN

In the following chapters the concept presented in Paragraph 2.3 will be designed in more detail.

3.1. Pinching plates

The principle of the pinching plate suspended by a cross-flexure is explained by Figure 12

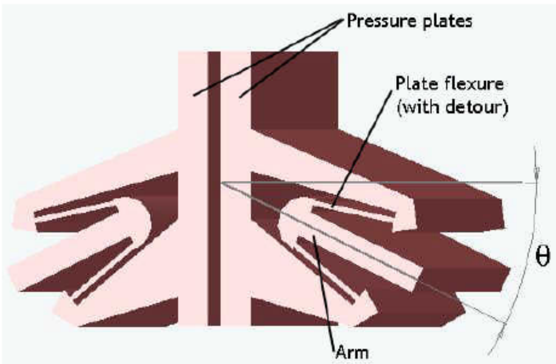

Figure 12: cross flexure on pinching plate

The plate flexures are situated such that they will always be under tension, by creating a "detour" for the compressive force. The point of rotation of the cross-flexure is exactly on the surface of the pinching plate.
The optimal shape for the pinching plate is a thick partitioned box, to give maximum stiffness. However, as explained in Paragraph 2.2 the point of rotation, which is on the surface of the pinching plate, should be close to the plate flexure. For this reason, the

plate flexures must closer to the surface of the pinching plate. A solution is presented in Figure 13 and Figure 14 where a deepening is made into the pinching plate. The deepening seriously affects the stiffness of the pinching plate, which is recovered by creating a connection through the arm.

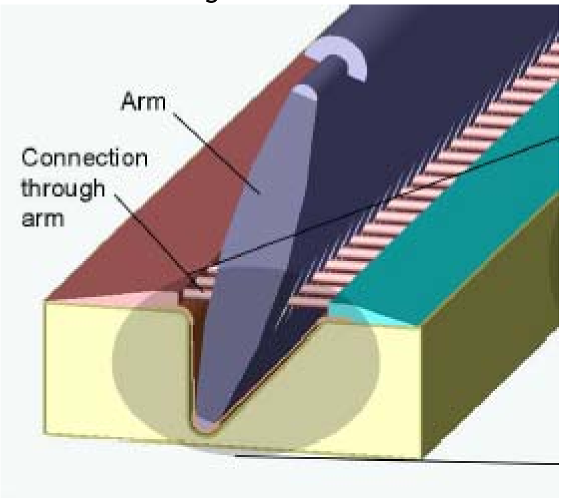

Figure 13: Deepening in the pinching plate

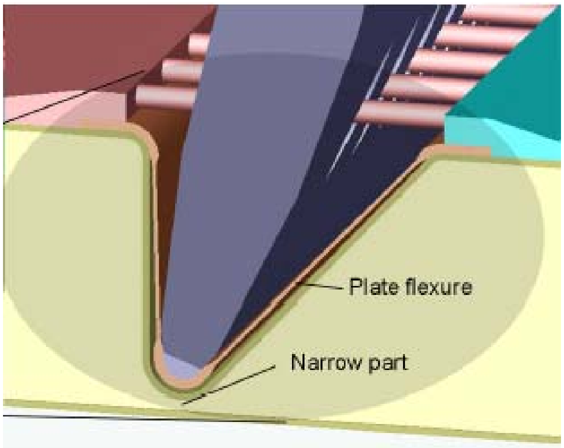

Figure 14: Deepening in the pinching plate (detail)

3.2. Arms

The arms will support the pinching plates and form the connection to the lateral connection. Like the pinching plates, the arm will be a partitioned box because high stiffness is required to prevent buckling under the large compressive force of 590 kN. A cross section of the arm is shown in figure Figure 15.

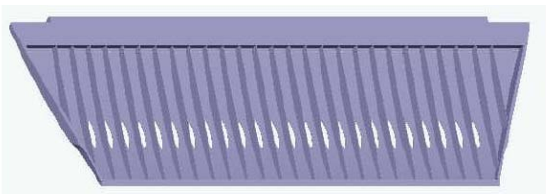

Figure 15: Cross section of arm

A reinforcement was required at the back end of the arm to increase the stiffness. This reinforcement is shown in Figure 16.

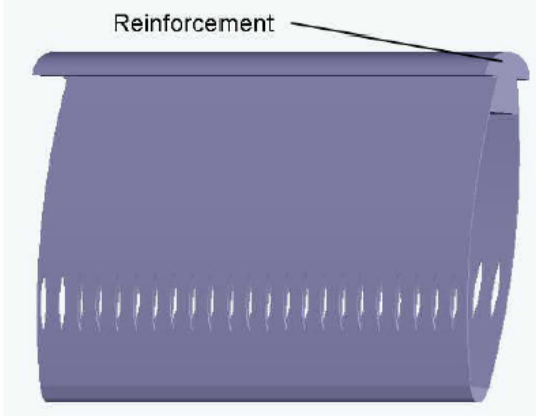

Figure 16: reinforcement of arm

3.3. Lateral connection

The pinching plates will have to be supported by a lateral connection. The lateral connection makes use of a new type of plate flexure, illustrated in figure Figure 17 and Figure 18

Figure 17: lateral connection

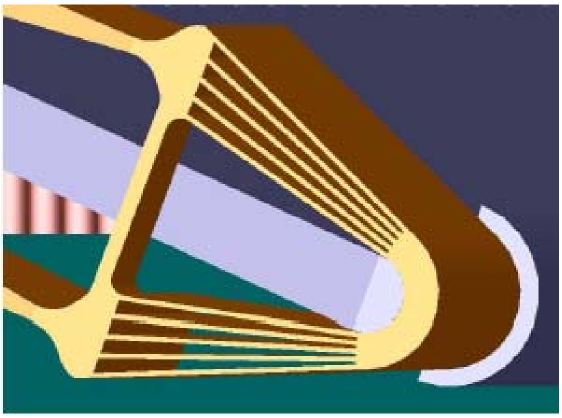

Figure 18: arm and lateral connection (detail)

3.4. Hydraulic actuators

Hydraulic actuators were selected to drive the tether deployer. Hydraulics have several advantages over electric motors for this design:

-High force density, allowing small components
-Slow motion without gearing
-No moving parts are loaded with the full load of the tether
One of the major disadvantages of hydraulics in space is leakage of oil in zero gravity. However, in the case of MARS-g, and other high tension tether applications, some gravity force will be present when the hydraulics are used.
The hydraulic actuators will be connected to the lateral connection as is shown in Figure 19.

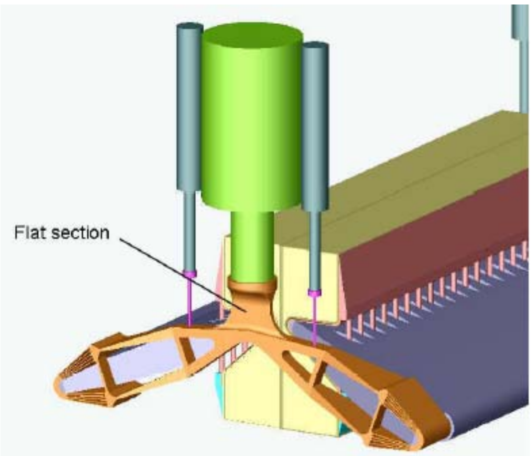

Figure 19: hydraulics

The large cylinder is used when the tension is high; the smaller cylinders are used when the tension is low.

3.5. System integration

Figure 20 presents an illustration of what the integrated system for MARS-g could look like.

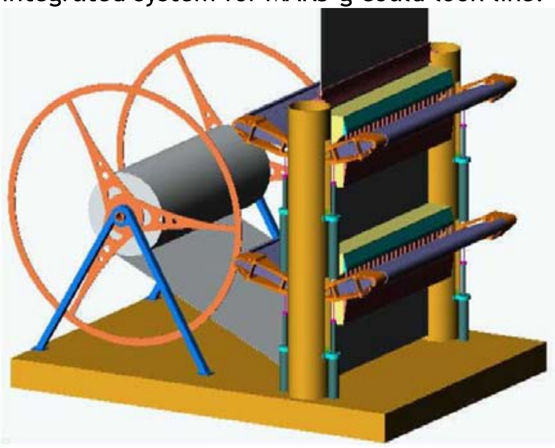

Figure 20: integrated system

3.6. Operations

While the pinching plates perform an alternating motion, continuous tether retraction is important for MARS-g. Figure 21 shows a motion-scheme that fulfills this requirement. The figure shows the motion of both pinching plates over time. When the line representing the motion is bold, that particular set of plates is holding the tether. In the time that the upper and lower lines overlap, the tension of the tether is transferred from one pinching plate to the other.

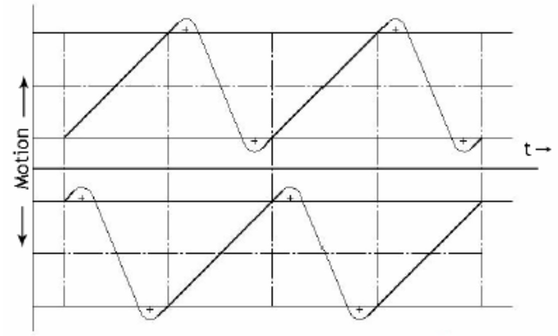

Figure 21: pinching plate motion vs. time

4. CONCLUSION

A novel, lightweight, high-tension tether deployer system is presented. Without bearings and gearboxes it will be easier to get space-qualified than other mechanisms that do use such components. Flexible hinges enable the presence of large forces in the mechanism. This design further strengthens the case for high tension space tether applications.

5. REFERENCES

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