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Deployment Simulation of Very Large Inflatable Tensegrity Reflectors

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Propulsion, energy collection, communication or habitation in space requires ever larger space structures for the exploration of our solar system and beyond. Due to the payload size restrictions of the current launch vehicles, deployable structures are the way to go to launch very large structures into orbit. This paper therefore presents the design and simulation of a tensegrity based structure with inflatable rigidizable tubes as compression struts. The literature review showed that inflatable structures are most promising for the development of deployable reflectors larger than twenty meters in diameter. Good compression performance and reliability can be achieved by employing rigidisable inflatable tubes. The concept presented in this paper will focus on the development and simulation of a one meter diameter hexagonal reflector substructure that can be easily expanded to larger diameters due to its modular design. The one meter diameter modular approach was chosen to be able to build a full size benchmark model to validate the numerical data in the future. Due to the fact that the tensegrity compression elements are not initiating at one specific location, a passive reaction gas inflation technique is proposed which makes the structure independent of any pumps or other active inflation devices. This paper will discuss the use of inflatable rigidizable elements and their counteraction with the rest of the tensegrity structure. Simulations have been undertaken to capture the deployment behaviour of the inflating tube while getting perturbated by the attached tensegrity tension cables. These simulations showed that the use of inflatable rigidisable struts in tensegrity assemblies can greatly decrease the system mass and stowed volume, especially for very large reflectors compared to conventional approaches.

I. ACRONYMS

CFRP	Carbon-Fibre Reinforced Plastics
CFRS	Carbon-Fibre Reinforced Silicone
DLR	German Aerospace Centre
IN-STEP	In-Space Technology Experiment Program (NASA)
LSTC	Livermore Software Technology Corporation
NASA	National Aeronautics and Space Administration
SMP	Shape Memory Polymer
TRL	Technology Readiness Level
TU	Technical University (Germany)
UV	Ultra-Violet

II. INTRODUCTION

Restricted by launch vehicle dimensions, deployable structures became necessary due to their low stowage and area density. For the success of future space missions involving large space structure, the development of new deployable structures and the improvement of current designs are of great importance. Applications can be easily envisioned through truss structures, masts, crew quarters, transport tunnels, large solar arrays, solar concentrators, solar sails or antennas. Scientific, discovery and telecommunication missions showed an especially high interest and demand for large reflective antennas recently. Common reflectors today are normally metal mesh or solid surface assemblies that are usually umbrella deployed. This deployment and surface type limits the size and frequency range of the current designs. To achieve large diameters, advanced structural concepts need to be applied to the surface and support structure. A valuable option for these large ultra light structures is the exploitation of inflatables. Reasons for the use of inflatable structures range from their low cost over exceptional packaging efficiency, deployment reliability, low stowage volume to low weight. Despite the fact that there has been no major leap on inflatable structure in space since the IN-STEP Inflatable Antenna Experiment[1] in 1998, research has been undertaken in various institutions all over the world in the field of inflatable structures[2-5]; new membrane materials have been discovered that can withstand the space environment, advanced simulation tools were developed that capture the highly non-linear behaviour of the inflation process and rigidization techniques have been investigated making the structure non-reliant on the inflation gas after deployment.[6-8] A novel concept is proposed to use a tensegrity sub structures for a thin foldable reflector dish. Tensegrity

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structures basically consist of strut elements for compression and cable elements for tensional loads. Tensegrity structures can be optimized for specific load paths and deployment sequences. Due to the fact that the stowed volume of a tensegrity structure is mainly governed by the size of the compression struts which can be disjoined.

III. DESIGN

For Strathclyde's Mirror Bees project[9, 10], that has the purpose of deflecting asteroids by solar sublimation, huge concentrators or reflectors (5-50 meters in diameter) are needed to collect enough energy to power the spacecraft's laser. Therefore novel design approaches are needed to be considered in order to achieve the necessary energy collection. The purpose of this design was to achieve expandability while considering the limitations given by the various launch vehicles nowadays. With the modular approach the spacecraft becomes independent of using one specific launch vehicle. This design is expandable first due to its highly compressible inflatable tubes and also due to its modular hexagonal shape; it is envisioned to build solar concentrators or reflectors up to 50 meters in diameter.

II.I Antenna Design

A tensegrity substructure is chosen as a baseline for the antenna design. In a tensegrity structure the compression loads are carried by strut elements and the tension loads are carried by cable elements. A tensegrity structure can be seen as an 'island of compressions in a sea of tension' [11]. For the reason of simplifying the comparison to past designs, the design of the antenna was based on a substructure of a hexagon tensegrity reflector developed by Dr. Gunnar Tibert in 2002.[12]

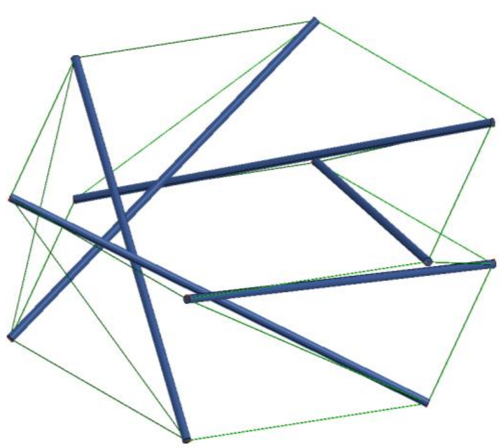

Figure 1: Tensegrity substructure for hexagonal reflector (isometric view)

The metallic mesh from Dr. Tibert's design was substituted by a Carbon-Fibre Reinforced Silicone (CFRS) membrane developed at TU Munich[13] in order to achieve the goal of obtaining a reflective surface suitable also for higher wavelength to concentrate the sun's energy. The CFRS membrane offers high dimensional stability with high in-plane and finite bending stiffness which makes the membrane easily storable. The effect of the attached membrane to the deploying substructure will not be covered in this paper due to the paper's focus on the deploying rigidisable inflatable strut elements. The developed structure in this paper should be seen more as a possible substructure to these CFRS membranes developed at the TU Munich.

It was decided to use a modular hexagonal substructure with a diameter of one meter and a height of 0.4 meters for this design analysis in order to have the possibility to build a real size benchmark model in the future to validate the simulation.

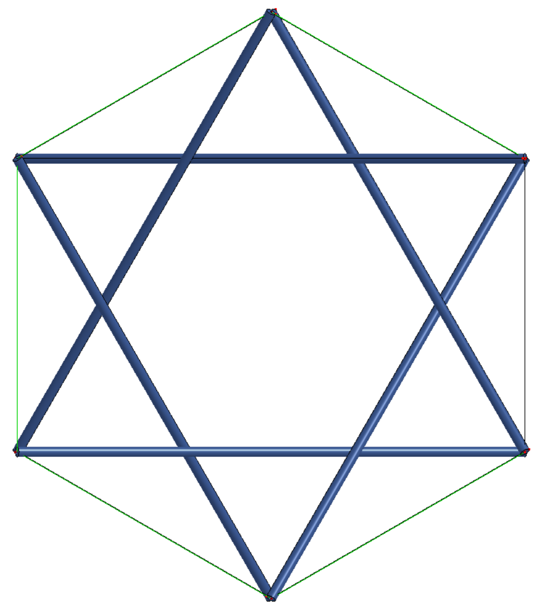

Figure 2: Tensegrity hexagonal substructure (top view)

From Figure 1 and Figure 2, it can be seen that the structure inherent six compression bars and 18 tension cables that add up to 24 bars. By using the inflation method to deploy the compression strut elements, the tensegrity substructure gets prestressed and can therefore be treated as a framework with pin-jointed bars. For this preliminary calculation it was assumed that the inflatable bars deploy and rigidize properly and can be treated as straight compression elements therefore. Various rigidization techniques will be summarized later in this paper.

With the hexagonal outline and the out of plane height, the structure has twelve frictionless joints (six on the top and six on the bottom). By using the extended Maxwell rule[14] and the number of kinematic constraints of six in three dimension, the number of states of self stress results in one which is a typical value for all tensegrity structures.

II.II Overview in Rigidization Technologies

In order to make the structure rigid and resistant to micrometeoroid and space-debris impacts[15], the structure needs to be rigidized from the flexible inflated state to a stiff rigid state. The rigidization also serves the purpose of obtaining a structure that is independent on the inflation gas after inflation. The rigidization technologies range from thermally cured thermosets to expandable aluminium film composites. The following overview should give a quick summary on available rigidization techniques today, it is not meant to be a detailed scientific explanation of each of the available technologies. For more detailed explanation on the technologies please refer to the references.

One option is the use of thermally cured thermoset composites that consist of a fibrous substructure impregnated with a thermoset polymer resin. By introducing heat by for example solar illumination or resistive heating, the resin will cure and rigidize the structure.[16]

The glass transition temperature rigidization is working in the way that the stored structure will be heated by the surrounding electronics and therefore stays flexible. As soon as the structure gets subjected to the cold space environment the structure becomes rigid.[17] The composites are also known as second order transition change or SMP composites. [16]

Another option are composites that cure in ultra violet (UV) light. The inflated structure is impregnated with a resin that will cure at certain wavelengths. The two ways of rigidizing the structure are either through the UV energy of the sun or the energy transmitted by UV lights embedded in the structure.[5, 18]

The use of plasticizer or solvent boil-off is another possibility to rigidize inflatable structures. The principle behind this technique is that a softening component in the resin evaporates once subjected to space environment and thereby regidize the composite.[16]

Foam rigidization fills the cavities of the inflating structure with structural foam that reinforces the structure once deployed.

The oldest technology is the aluminium and film laminate rigidization technology which was used in NASA's ECHO II program in the 1950s. The laminates used for this approach consist of thin laminates made from ductile aluminium and polymeric film. The principle behind this technique is to stretch the aluminium beyond the alumiums hardening stress. After stretching, the pressure is released and the aluminium is in a compressive stage while the polymer is still in its elastic range, the result is a rigid structure.

Despite all the advances in the field of rigidization technologies, no in space rigidization on any inflatable structure has been performed up to this date. One of the biggest problems with the ridization is that in a real life application the rigidization will most likely be uneven which creates distortions in the shape of the reflector that are almost impossible to predict or simulate.

II.III Inflation Techniques

The inflation of the tubes offers a big problem for this kind of structure due to the existence of a large amount of non connected inflating components. Additionally, these inflatable bars aren't initiating from one central feeding point where a single pump could inflate these tubes, every bar would need to have its own feeding pump. Having a single feeding pump for every tube would complicate the entire system which would not inherent any improvement to the conservative techniques available today. To simplify the design, it was envisioned to use a passive inflation system like the inflating gas reaction method for example. The inflation gas reaction method uses a coating that undergoes a phase-change in vacuum conditions or a powder that sublimes into gas to provide additional vapour pressure to the inflating structure. [19, 20]

III. SIMULATION

III.I LS-DYNA

The program used for the simulation of the inflatable system was LS-DYNA by Livermore Software Technology Corporation (LSTC). LS-DYNA is a popular simulation tool for inflatable structures in the industry, mainly for airbag deployment simulation. Another reason why LS-DYNA was selected for this kind of study was its availability with an ANSYS/LS-DYNA academic license at the University of Strathclyde, Glasgow, UK.

III.II Simulation Set-Up

The inflating tube was modelled in the LS-DYNA pre-processor LS-PrePost.

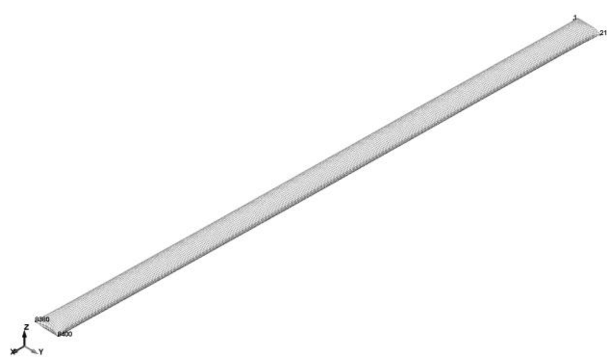

Figure 3: Flat tube and after inflation

The tubes were modelled as two rectangular sheets connected at the edges with an initial distance of one millimetre before inflation. The elements on two corners of the tube were constrained (Node 1 and 21 in Figure 3). The number of shell elements is 20 along the width and 400 along the length of the tube.

For the tensegrity cable simulation, the cables were attached on the two corner elements of the free edge and constrained at a fix point on the other side (Node 8380 and 8400 in Figure 3). Each cable was modeled with 100 beam elements.

The control volume method was used for the inflation simulation of the compression tubes. Further research will be focused on applying the particle method that should give more precise results. For the control method approach it is necessary to define a mass flow of the inflating gas into the structure. The inflation will be triggered by the increased volume from sublimating powder by subjecting the structure to a reduced pressure environment as it exists in space. With this approach there is no actual mass flow of inflation gas into the structure. Further research will be undertaken in developing tools for LS-DYNA to predict the gas reaction method in vacuum conditions more accurately. By using the control volume method and applying it to the entire structure, a similar inflation characteristic then the residual air method can be achieved because the entire volume will expand without starting at one specific initial point.

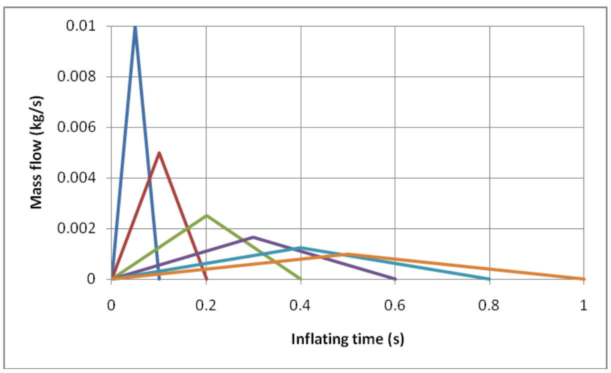

Figure 4: Assumed mass flow into inflating structure

The mass flow required for the control volume method was calculated by employing simple tube geometrics and thermodynamic equations by using the assumption of dealing with an ideal gas. The volume of the inflatable tube is approximately 796 cm^3 which lead to an inflating gas mass of $473x10^{-6}$ kg by assuming a pressure difference between the inner structure and vacuum environment of 50000 Pa. A triangle shaped mass flow characteristic was selected over the rectangular progression because of the nature of the reaction gas method which will probably start slowly when the first powder sublimates, leading to a maximum and slowing down afterwards again until all powder is sublimated. Figure 4 shows different mass flow characteristics for an inflation time of 0.1, 0.2, 0.4, 0.6, 0.8 and 1 seconds to obtain an inflation gas mass of approximately $500x10^{-6}$ kg

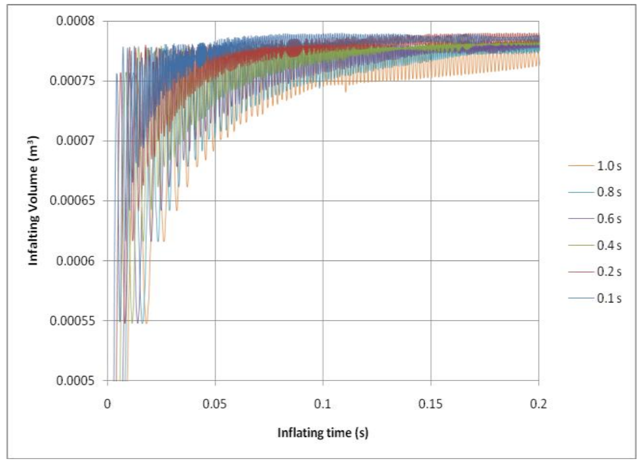

Figure 5: Oscillation of inflating volume for various inflation times

Figure 5 shows the performance of the structural inner volume while subjected to various inflation times which are outline more in detail in Figure 4. It can be seen in the simulation of the structure in LS-DYNA and the volume plot that the structure is oscillating during the entire inflation process. The simulation showed that with slower inflation rates, the frequency of the structural vibration is decreasing but the magnitude of the amplitude is increasing. For further folding simulation it was therefore assumed to continue with a shorter inflation time, a triangular inflation time of 0.2 seconds and a peak of 0.005 kg/s (red line in Figure 5) were chosen therefore.

<u>Material</u>

The decision was made to use Mylar as a membrane material. The chosen Mylar has a Young's modulus of 4,805.2 MPA, a density of 1390 kg/m^3 and a thickness of 0.05mm. Kevlar 29 was used for the tension cables with a tensile modulus of 70,500 MPa, a density of 1440 kg/m^3 and a diameter of 1mm. These materials were chosen mainly due to their low density and high stiffness which results in a minimum mass that is of great importance for space structures. The length of the strut elements was assumed to be one meter with a width of 5cm in order to ease the comparability and to assemble the above mentioned hexagonal tensegrity reflector.

Folding

The big advantage of inflatable structures is that they can be stored in a very small stowage volume due to their folding capabilities. In this paper two folding principles where investigated, the first folding pattern that was considered was the spiral folding pattern and the second one was the thin z-fold. The airbag folding keyword *ABfold was used in the LS-DYNA pre-processor LS-PrePost. The spiral fold is independent on the number of folds which should make the comparability to other designs much easier then the z-fold. Figure 6 shows the spiral folded one meter tube with a distance of 0.1mm between the surfaces.

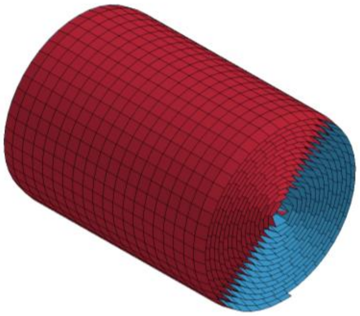

Figure 6: Spiral folded tube in LS-PrePost

The other folding method used in LS-PrePost was the thin fold to establish a z-fold. Investigations have been undertaken in folding patterns of 2, 4, 5, 8, 10 and 20 folds. A folding amount of 20 folds would lead to a package size of the one meter tube of 5cm by 5cm.

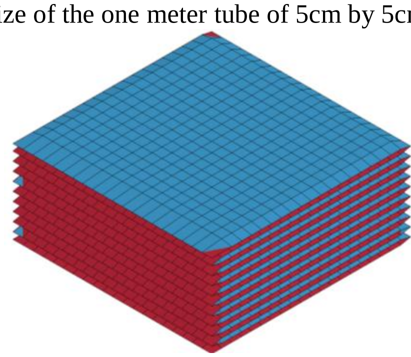

Figure 7: Z-fold with 20 folds in LS-PrePost

IV. RESULTS

IV.I Folding

Spiral Folding

The LS-DYNA simulation showed that the spiral folding pattern results in a chaotic unpredictable deployment with out of plane distortion of the deploying structure. Figure 8 shows the deployment at 0.016 seconds and it becomes obvious that employing the spiral fold would obtain a too high risk of entanglement with the inflating tube itself and the surrounding environment. It can be also seen that the tube is developing knots by itself due to the tight wrapping.

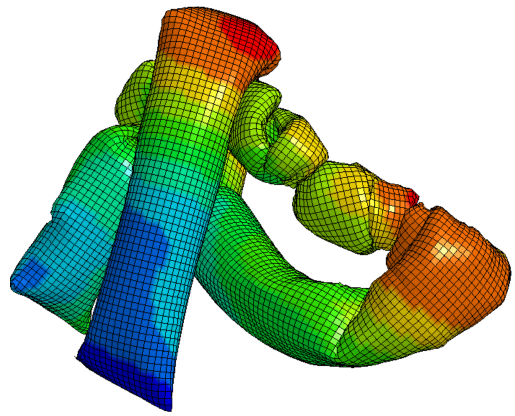

Figure 8: Deployment of spiral folding at 0.016 seconds

Furthermore, the high curvature of the spiral fold elongates the top and shortens the bottom surface elements. This deformation results in different initial dimensions of the top and bottom surface elements which creates slightly bended deployed tube and not straight tube which would be the correct solution. A solution to this problem would be to roll the tube on a cylinder structure with a non-infinitesimal small diameter which will ease the deployment and simulation. The big disadvantage of this principle is the comparably high storage volume because of the dead volume inside the cylinder. The folding pattern and deployment scheme is based on the rigidized inflatable deployable CFRP boom developed by the DLR[5]. The boom consists out of a hollow skin made with very thin CFRP material which is stowed by coiling. An inflatable tube inside the CFRP boom deploys the structure.

Z-fold

The simulation of the z-fold on the other hand obtained better results than the spiral folding deployment simulation.

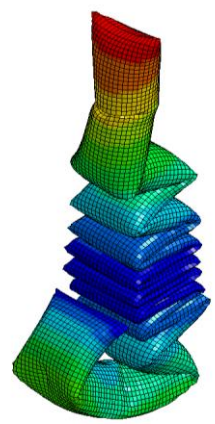

Figure 9: Deployment of 20 times z-fold at 0.014 seconds

The simulation showed that by increasing the folding number the oscillation of the inflating structure can be reduced. Another observation that was made was that the by increasing the number of folds, the direction of the deploying tube can be predetermined more accurately then with lower folding numbers.

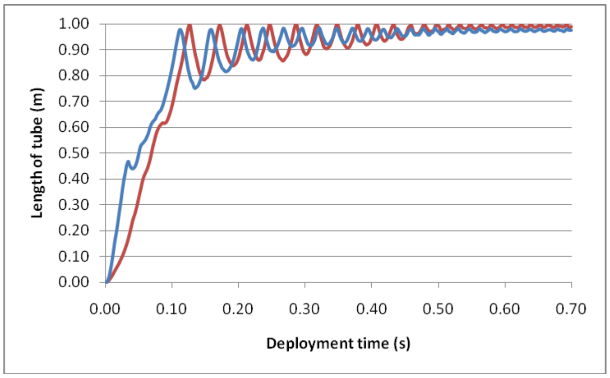

Figure 10: Deployment performance for a twice y-fold (red) and 20-times z-fold (blue)

The deployment performance of a two times folded and twenty times folded tube can be seen in Figure 10, the graph shows that the twice folded has a similar oscillating frequency then the 20 fold but the magnitude is slightly higher especially in the middle phase of the deployment. Deployment simulation with the 4-fold, 6-fold, 8-fold and 10-fold showed a similar trend of decreasing oscillating magnitude by increasing the fold number.

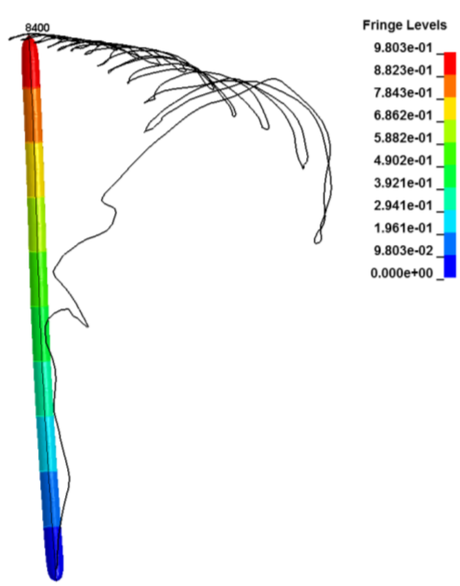

Figure 11: Trace of top element during deployment

Another interesting observation is the small dent in the 20-times fold curve at approximately 0.045 seconds. At this time all the folds are disintegrated into one residual fold and the loosening of this last fold introduces a shock wave that travels through the structure which results in a compression and therefore shortening of the outer structure.

Figure 11 shows the trace of the top edge element of the inflatable tube for a full deployment cycle. It became obvious during the simulations that with increasing folding number the precision in the deployment direction can be increased as well. The initial stack of the folded tube in Figure 11 came from a horizontally lying tube which was then folded to a vertical stack. The trace line in Figure 11 and the deployment graph in Figure 10 also show that the tube is deploying rather quickly and straight in the first 0.1 seconds before passing over to the oscillation phase that commences full vertical deployment of the tube.

IV.II Strings attached

In order to obtain a tensegrity structure further research was carried out to simulate the tension cables attached to the inflating compression elements. For this simulation the 20 times z-fold described above was used as a base element. The Kevlar cable were attached to the top corner elements at one end and constrained on the other end at a distance of one meter in the line parallel to these elements in the initial folded condition.

The simulation showed that the twenty times folded tube deploys first into an only single folded tube as can be seen in Figure 12, which shows the deployment simulation at 0.3 seconds. The tube is deploying to this state after roughly 0.1 seconds. After this tube deployment, the inertia of the attached cable slows down the deployment.

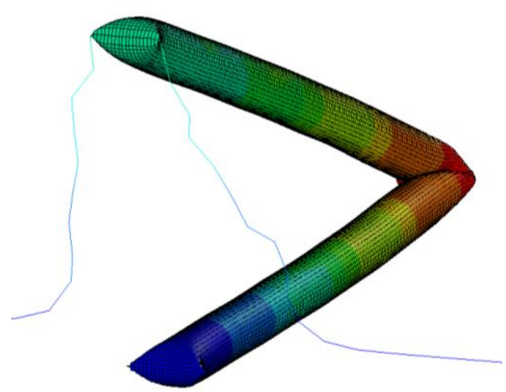

Figure 12: Deployment with strings attached

Figure 13 shows the height of the deploying 20 fold tube with two strings attached. Full deployment is achieved after 1.3 second. After the full deployment is obtained, the structure still oscillated because of the counteraction of the attached strings.

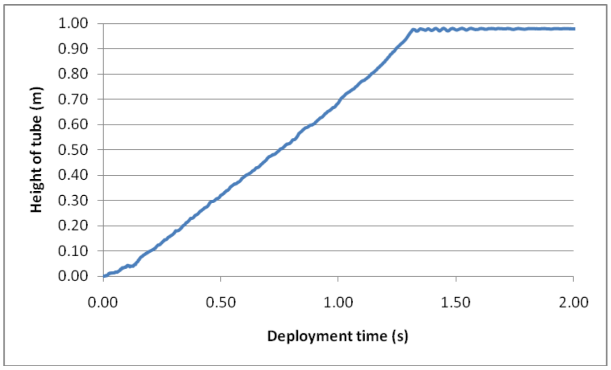

Figure 13: Height of deploying tube over time with two strings attached

A big issue with these inflatable tensegrity structures is the problem of entanglement of the strings with the deploying tube. The simple design presented in Figure 1 and Figure 2 with its six inflating tubes already has 18 cables that would result in an enormous entanglement risk if the cables would be loose. An idea to overcome this risk is to use a device that would store the cable and slowly released them when needed. An example of this device is the widely commercially available storable extension cords, like the USB cable storage for laptop mousses. The USB cable for an ordinary laptop mouse can be seen in Figure 14.

Figure 14: USB extension cable storage

V. CONCLUSIONS

The research presented in this paper outlines the unique possibility that inflatable structures can have in the field of space structures. It can be concluded that LS-DYNA is a great tool for the simulation of inflatable structures with countless possibilities. The simulation undertaken in this paper showed that the deployment of a z-fold structure is much more reliant then the spiral folding method. By winding the tube around a cylinder, the spiral fold might be more robust but it greatly reduced the volume efficiency of this kind of fold. The simulations also showed that by increasing the number of folds the deployment direction can be determined easier. By increasing the number of folds the oscillation magnitude before final deployment can be reduced and the deployment direction can be predicted more precisely then lower folding numbers. Further research will focus on more precise inflation tools to simulate the residual air and sublimating powder inflation more accurately because the control volume method was used in this paper was just to simplify the simulation. In the authors view it is of great importance for the future success of inflatable structures that more flight opportunities are given to inflatable structures to increase their technology readiness level (TRL) in order to become a main building stone for space missions to moon, mars and beyond.

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