Numerical simulations of an inflatable/rigidizable balloon for electronic collection

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Abstract

Inflatable space structures have been studied without a great success in the past 30 years. Now, due to the new computer-aided design techniques and the developments of new advanced materials, they are becoming one of the most promising technologies for the realisation of very large structures in space. In fact, inflatable structures present very low volume/weight ratio at launch that could significantly reduce the launch cost. In addition, their structural simplicity results in an improved reliability with respect to conventional structures [1].

In this paper the results of the numerical simulations made on an inflatable balloon of 5-meter diameter will be presented. The balloon is made of a multilayer membrane of Kapton™ and copper and is rigidized by yielding the metallic layer through the inflation pressure.

A key feature of this rigidization technique is the control of the deployment and the pressure inside the structure. The aim of the simulations carried out in this work was to assess the right material thickness and inflation pressure and determine the most suitable pressure profile. A pressure too low could not yield the material resulting in insufficient structural stiffness after the gas purging. On the other hand, a pressure too high could damage the very thin material. Both the inflation and the purging phases were analysed to assess the behaviour of the material. Simulations were performed with different values of pressure, pressure profiles, material thickness and layers configurations.
1 Introduction

In view of large number of commercial and military satellite constellations that are being planned for LEO operation, need for removing them at the end of their operational life has gained urgency. An unacceptable risk of potential collision is created by their presence in a narrow band of orbital elements. Use of electrodynamic tethers has been proposed, as an alternative to carrying the additional propellant required for deorbiting the satellites. Such systems are shown to compare favourably to the conventional propellant-based systems in terms of mass, and indeed, there is no limit to the mass of the satellites that can be deorbited, as the only penalty for larger masses is longer re-entry time. However, the key to the successful utilisation of the electrodynamic tether for deorbiting lies in minimising the length and the mass of the tether itself. It has been shown that utilising a balloon of sufficiently large size at the end of the tether can effectively reduce both of these. By providing the additional surface area for the collection of charged particles the balloon reduces the required length of the tether, which is now controlled by the required gravity gradient force on the system. This paper will discuss the issues associated with the design of the balloon, its integration with the tether and the spacecraft and its deployment characteristics. In doing so the feasibility of the overall concept is established [2].

The principle of operation of the electrodynamic tether with a balloon at one end is shown in Figure 1. When a conductive tether in a geomagnetic field moves across field lines, an EMF is induced between the ends of the tether. If an electric current flows in the tether by providing the lower end of the tether with a way to release electrons, a force (Lorentz force) is created on the tether. The tether experiences either acceleration (thrust) or drag depending on the current direction.

![Figure 1: Functioning scheme of the system](image-url)
2 Electrodynamic simulation

The balloon will be built using a multilayer material made of Kapton™ substrate, on which a copper layer is deposited. The rigidizing method consists of yielding the metallic layer through the application of an internal pressure, which is also used for the balloon deployment. Copper was chosen for the coating because, while it weighs more than other materials viable for this purpose, such as aluminium, its oxide is conductive. So it presents the advantage that, should an oxide layer be present on the metallic surface, the system will keep working even with reduced performances. The copper layer should however be as thin as possible in order to:

- Make the folding process easier, thus reducing the volume needed for the system stowage.
- Keep the pressure necessary for the deployment and rigidizing process of the structure as low as possible. This allows using a minimum amount of gas for inflation reducing the mass of the inflation system.
- Lower the material stiffness in order to prevent the formation of folds that could become wrinkled. Those wrinkles could compromise the electrical continuity of the metallic layer and the integrity of the balloon itself.

The optimal thickness of the material would be about 1 micron of copper on a substrate of 12.5 micron of Kapton™. Such a material has, however, a very high electrical resistance. In fact considering that the maximum current flowing through the balloon will be about 3 amps, a high electrical resistance value leads to very high power dissipation with consequent high temperature on the balloon surface. In addition this causes a strong voltage drop on the balloon, which reduces the system performances.

An electrodynamic characterisation of the balloon was carried out in order to assess the optimal thickness of the metallic layer. In particular the electrical resistance and the voltage drop due to this resistance were studied. The resistance of the whole balloon was calculated as a function of the thickness of the metallic layer. The results are shown in Fig.2. As can be seen, to keep the total resistance under 100 Ohms, a copper layer over 5 microns thick is necessary. Such a thickness implies the use of a very stiff and massive material. However it is to be noted here that in the top half of the balloon the collected current, which flows on the metallic layer, is very low; thus even high electrical resistances will not cause high voltage drop and the corresponding high power dissipation.

Another analysis was then carried out to assess the voltage drop due to resistance at each point of the balloon. The hypothesis of constant charge collection on the whole balloon was made. The analysis was repeated for several values of the copper thickness. The results are shown in Fig.3. As can be easily seen that the profiles of the voltage drop have a hyperbolic behaviour, increasing toward the point of connection with the tether at bottom end of the balloon. Correspondingly the voltage drop is virtually infinite for any value of the
metallic coating thickness. This is because the entire current collected by the balloon must flow through a point, which has zero area and therefore infinite resistance. Beyond this theoretical limit, it can also be seen that, at a finite distance from the connection point, there are huge and totally unacceptable voltage drops. For this reason, a thick plate in which the current could flow easily towards the tether must be located at the bottom side of the balloon.

Figure 2: Total electrical resistance as a function of metallic layer thickness.

Figure 3: Voltage drops and collected current on the balloon.
Figure 4: Power dissipated along the balloon.

Table 1: Voltage drop for different plate diameter and copper thickness

<table>
<thead>
<tr>
<th>Radius</th>
<th>Current</th>
<th>1 μm</th>
<th>1.5 μm</th>
<th>2 μm</th>
<th>2.5 μm</th>
<th>3 μm</th>
<th>3.5 μm</th>
<th>5 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>2.99</td>
<td>265.04</td>
<td>176.69</td>
<td>132.52</td>
<td>106.02</td>
<td>88.35</td>
<td>75.73</td>
<td>53.01</td>
</tr>
<tr>
<td>0.25</td>
<td>2.99</td>
<td>246.03</td>
<td>164.02</td>
<td>123.01</td>
<td>98.41</td>
<td>82.01</td>
<td>70.29</td>
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<tr>
<td>0.3</td>
<td>2.99</td>
<td>230.63</td>
<td>153.75</td>
<td>115.31</td>
<td>92.25</td>
<td>76.88</td>
<td>65.89</td>
<td>46.12</td>
</tr>
</tbody>
</table>

In Table 1 the voltage drops and the collected current for several thickness of the metallic coating and for three radii of the plate are listed. As can be seen, with a plate of 0.3-meter diameter the voltage drop is acceptable even for the smallest thickness.

The plate also works as a support for the deployment system of the tether, the inflation system of the balloon and the electronic control devices for them. For this reason it must have a sufficient stiffness to carry the mass of these systems. Notice that a copper plate of 0.3-meter diameter 0.8mm thick weighs 2 Kg. A plate made with a honeycomb material is also being considered. It weighs less but presents some problems about the tether connection. The collected current and power dissipated by the balloon without plate are shown in Figure 4.

Form the results of the analyses carried out it can be concluded that the optimal thickness of the copper layer should be 2.5 microns. This value allows having good mechanical properties and at the same time the material is able to let the current flow toward the tether without losses and dissipation being too high.

3 Thermal analysis

A thermal analysis was carried out in order to evaluate the temperature field on the surface of the balloon during its operational life. This analysis is also
In the analysis the typical thermal load in LEO orbits were considered which are:

- Direct solar radiation.
- Albedo radiation.
- Earth radiation.
- Balloon’s thermal radiation.
- Heat from the ohmic dissipation on the balloon surface.

The temperatures over an entire orbit were analysed to evaluate the differences between the daytime and the eclipse period. In Fig. 5 the temperature profiles for the four identified points of the balloon are shown. The simulation was repeated for different values of the copper thickness but the results were quite identical because the mass/surface ratio is in any case very low. The sharp temperature variation, seen when the system crosses the day-night line, could cause adherence problems between the two layers of the material. However, the difference in the thermal coefficient of expansion of Kapton™ and copper ($\alpha_{\text{Kapton™}}/\alpha_{\text{Copper}}=0.89$) and the number of cycles (about 1000 for a deorbiting period of 1 month) are not considered to be sufficient for this to be of concern.

### 4 Numerical simulation of the inflation process

In order to carry out these simulations, the MARC FEM code was used. The balloon is made of a laminate of Kapton™ and copper. The lay-up of the composite is shown in Fig. 6. As can be seen the copper layer is very much thinner than the Kapton™ layer. The thickness considered for each layer is also
given in Fig. 6. For the seams a doubled Kapton™ thickness was considered (2 x Kapton™ layer), i.e. $25 \times 10^{-3}$ mm.

The simulation was done with a quasi-static non-linear transient solver. The boundary conditions applied to the system were:

- Symmetry conditions at the edges of the structure in order to simulate the whole balloon with only a 1-quarter mesh.
- Constraint on all the nodes of the bottom edge in order to simulate the plate and avoid rigid motions.
- Internal pressure on all the faces of internal layer (Kapton™)

In particular, a time dependent profile was used for the applied pressure as shown in Figure 6. The maximum value in Figure 7 corresponds to a pressure of 150 Pa and 300 Pa for the simulations. Such a profile was used in order to simulate both the inflation and the purging phases. The simulation time was 10 sec with a time step of 1 sec.

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**Figure 6: Lay-up and mechanical properties of the balloon’s material**

- **COPPER**
  - Isotropic
  - Layer thickness: $2 \times 10^{-4}$ mm
  - Young’s modulus: $1.17 \times 10^{10}$ Pa
  - Poisson Coeff.: 0.33
  - Density: $2000 \text{ kg/m}^3$
  - Yield tension: $6.4 \times 10^6$ Pa

- **KAPTON**
  - Isotropic
  - Layer thickness: $12.5 \times 10^{-4}$ mm
  - Young’s modulus: $2.3 \times 10^9$ Pa
  - Poisson Coeff.: 0.38
  - Density: $1420 \text{ kg/m}^3$

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**Figure 7: Profile of the applied pressure**
4.1 Simulation results

When the pressure is applied both the copper and Kapton™ layers resist the load. But, due to the very small thickness of copper coating, the pressure needed to yield is very low and this value is reached almost instantaneously. From this point onward the copper does not support any significant fraction of the load because of its very low plastic modulus. Figures 8 and 9 show the maximum displacement on the balloon surface for the maximum inflation pressure of 300 Pa and 150 Pa respectively. The scale of the graph is in meters and the deformations are in actual scale.

The elastic strain in the copper layer is nearly zero. The deformation grows very fast and reaches its maximum at the maximal applied pressure. At this point the copper also reaches the maximum value of plastic strain (Figures 10 and 11). During the purging phase the copper does not tend to recover its plastic strain but the Kapton™ below it, which displays a perfect elastic behaviour, recovers all of its deformation and drags back the copper along with it. For this reason the copper is likely to be compressed by the Kapton™ film and it is forced to deform plastically over its natural level. The plastic strain in the Kapton™ is equal to zero in the whole balloon because this material is defined to be perfectly elastic. In Figure 12 the displacements of the two nodes on the surface of the balloon during the inflation process is depicted. In this figure node 851 is on the mean line of the gore and node 284 is on the seam and they seem to closely follow the pressure profile.

As noted above, the maximum displacement is achieved in correspondence to sixth increment when the pressure reaches its maximum value. Furthermore, as can be seen each gore displays the largest displacement on its mean line. This result shows that the seams act as a restraint with respect to the laminate material. In fact, after the yielding of the copper layer in the laminate, due to its plastic modulus, only the Kapton™ resists the load. And because of the doubled

![Figure 7: Displacement of two nodes during the inflation process very low](image-url)
thickness of the Kapton™ in the seams, they become stiffer than the laminate material. The displacement at the centre of the gore is larger than on the seam for every value of the pressure (in Figure 7 node 851 is on the mean line of the gore and node 284 is on the seam).

Figure 8: Displacement at maximum inflation pressure: 300 Pa

Figure 9: Displacement at maximum inflation pressure: 150 Pa

Figure 10: Plastic strain after purging (inflation 300 Pa)
5 Conclusions

Through the analyses carried out it was possible to determine the right thickness of the metallic layer in order to achieve a good compromise between the electrodynamic and mechanical properties of the structure. The FEM simulations showed that it is possible to model the process that takes place during both inflation and purging phases. It has been highlighted how the seams of the balloon act as a restraint with respect to the laminate material. Furthermore, it has been seen how the copper layer yields uniformly and in a controllable way. In fact with the presented FEM model it has been possible to determine the right inflation pressure. The results showed also that there are interlaminar stresses especially during the purging phase due to the different properties of the materials. However it has been not possible to highlight eventual buckling phenomena in the material once unloaded. These effects were also noted after the experimental mechanical tests on the material itself and must be explored further.

References
