Simulation and Analysis of Butterfly-inspired Eclosion Deployable Structure

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Abstract. Deployable structures, as an important kind of structure, have been widely used in a variety of satellite antennas and space reflectors. The research of deployable structures usually faces a series of theoretical and technical challenges because the size and mass are not only the limitations of deployable structure but also the key issues in the design process. Nevertheless, the appearance of bionic provides a new concept to develop the deployable structures. Inspired by the eclosion and development of butterfly wings, a bionic inflatable deployment structure has been presented in this paper. The whole system of emulate model is established and has a simulation analyzed with the help of dynamic analysis software. This simulation is aimed at emulating the deploying process, and calculating the stress distribution of the structure. Then some relative curve fitting is conducted on the deploying trajectory. A prototype has been fabricated and tested to be able to deploy smoothly and steadily.

Introduction

With the continuous improvement quality of people's life and the quick development of science technology, deployable structure has been widely used in our daily life and varieties of scientific research fields. Deployable mechanism can change from the folded state to the unfolded, in order to obtain a larger working surface [1]. The structure can be easily transported and stored in the folded state and the larger working surface can be achieved after expansion. As for the deployable structure’s form and deployment process, the deployable structures play an important role in the field of aerospace and a higher requirement has been put forward[2,3]. Because of dimensional constraints dictated by the finite size of the launch vehicle, large spacecraft appendages have to be stowed during launch and fixed on the vehicle payload compartment in a state of folding, such as, satellite antenna, spacecraft solar array, and other space structures [4-6]. When they were launched into orbit, they would be controlled by the ground command center to develop gradually from the smallest volume to become a large and complex space structure, which was designed in requirements, and then locked and maintained for the operation state. So the space inflatable structures have several requirements, such as much lighter weight, higher packaging efficiency, simpler design with fewer parts, and higher deployment reliability. In view of this problem, looking for an effective design method is the top priority.

Biomimetic engineering is an effective design approach because the forms and driving mechanisms of animals and insects are highly efficient and robust [7]. According to this characteristic, to design an efficient and reliable deployment structure which was inspired by bionic principle has become research hotspots [8,9]. In biology, insect eclosion expansion has a unique characteristic. For insects’ eclosion, the most complete and representative case is the lepidoptera insect (such as butterfly) metamorphosis [10]. In the process of eclosion, it shows that the wings
change from small to big, soft to hard. The body surface area of pupae will have a great difference with that of adult insect which has been formed during the eclosion [11]. This feature can be used for bionic space deployable structure’s design. Therefore, a bionic inflatable deployment structure is designed in this paper based on the principle of the butterfly eclosion.

**Research on Bionic Modeling and Simulation**

Recently, the researchers have carried out extensive research on the bionic deployment structures. However, the eclosion deployment of insects has gradually entered into people's horizons along with the ongoing research. And the eclosion process attracts more and more attention by its unique advantages. Typical examples of lepidoptera eclosion are shown in Fig. 1.

In the comparative study of these insects eclosion, a phenomenon was found that the butterfly eclosion process is very representative. So based on the characteristics of the butterfly eclosion, the research on a series of deployable structure has been carried out in this paper.

**The Eclosion and Development Process of Butterfly.** Some important information is recorded, such as the way of butterflies emerging from the pupae and spreading their scaly wings, the process of veins’ hardening, and the development of scaly wings’ changing from small to large, soft to hard. A conclusion can be achieved that eclosion of butterfly is using of blood pressure to burst the pupae through analyzing all of above behavior. The whole body separates itself from the puparium with the help of the body fluid’s pressure and its own body’s twist [13]. Right after the eclosion, the adult’s wings are very plicate, soft and tender. With the hemolymph liquid inflowing into the wings through veins, the wings expend gradually, and the veins harden into tannin. As shown in Fig. 2.
The study found that veins of butterflies’ scaly wings play an irreplaceable role in the expansion process. When scaly wings are in the pupae, the veins are clearly visible under a microscope through dissection. As shown in Fig. 3.

![Veins in pupae](image)

**Fig. 3 Veins of scaly wings in the pupae**

**The Establishment of the Bionic Model and Simulation.** After the scaly wing’s total expansion, the veins can be observed clearly from the outside. The whole scaly wing is fanwise and its veins spread in divergence along the wing. Such structural characteristics provide some useful inspiration and methods to design inflatable deployable structures. In order to simply the complicate distributed veins in the scaly wing, the main veins are extracted to hold and connect the thin-films. With this idea the 3D model is built and the external pictures of the real scaly wing and the model are compared as following Fig. 4.

![Veins and model](image)

**Fig. 4 The appearance of butterflies’ scaly wing and simulation model**

Specific to the eclosion development feature and the scaly wing structure of butterflies, several primary veins are chosen out to model and simulate the whole developing process, from the butterfly’s emergence out of the pupae to the scaly wing’s total tanning. First, a 3D model of thin walled cavity and filmed structure is built in Solidworks software, with a 330mm-length and a 80mm-width. In order to simulate the inflatable deployment process, a simulation model is established for the coiled state. Then the 3D model is imported into Hypermesh to mesh and the finite element model of the flare angle is shown in Fig. 5.

![Finite element model](image)

**Fig. 5 The finite element model with coiled state**
During the inflation, there is an optimal pressure in the deployable structure. A deviation from this value will either lead to a large deformation by the excessive inflation pressure, or result in lots of wrinkles caused by insufficient pressure [14]. Its internal optimal inflation pressure is defined as Eq. 1,

\[
P = \frac{4 \sqrt{2} \frac{n}{\pi} \arcsin \left(\frac{\sin \frac{\pi}{n}}{\sqrt{1 + \cos^2 \left(\frac{\pi}{n}\right)}}\right) - 1}{R(1-\sigma)}
\]

where \( n \) is the number of triangle elements, \( t \) is the film thickness, \( E \) is the elasticity modulus, \( R \) is the radius of curvature and \( \sigma \) is the Poisson’s ratio. As the elements number of this model is considerable, Eq. 2 can be obtained by simplifying Eq. 1 and used to calculate the internal pressure,

\[
P = \frac{2\omega^2 Et}{3RD^2(1-\sigma)}
\]

where \( \omega \) is the widest element and \( D \) is the structure’s aperture. The parameters of thin film are listed in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>E</th>
<th>( \sigma )</th>
<th>( \rho )</th>
<th>( t )</th>
<th>R</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>270  [MPa]</td>
<td>0.3</td>
<td>( 1.45 \times 10^3 ) [kg/m(^3)]</td>
<td>0.1 [mm]</td>
<td>230 [mm]</td>
<td>330 [mm]</td>
</tr>
</tbody>
</table>

The optimal inflation pressure for film tension is aimed to completely eliminate membrane folds. Considering the small size of the structure and the gravity effect, 5 Pa air pressure is suitable for inflation.

The structure of inflatable membrane tube bending can be considered as a Bernoulli - Euler elastic cantilever beam bending model, whose differential equation is as following,

\[
\frac{d^2 y}{dx^2} = \frac{M + 2\sigma pr^3 \sin \phi}{Etr^3[(\pi - \phi) + \sin \phi \cos \phi]}
\]

where \( y \) is the beam displacement, \( x \) is the element local coordinate, \( M \) is the bending moment of fold point, \( r \) is the tube radius, \( p \) is the air pressure in the tube and \( \Phi \) is the flare angle. The relationship between \( M \) and \( \Phi \) can be obtained by simplifying Eq. 3, as following,

\[
M = \pi pr^3 \left[ 1 - \exp \left( -\frac{3.12Et}{p} \tan \frac{\phi}{2} \right) \right]
\]

For the virtual prototype model, the maximum bending moment at the folding point is \( M_{\text{max}} = 1.6N \cdot mm \). According to Eq. 4, when the internal intensity of pressure is 5Pa, the resultant moment at the folding point of the film is \( \Sigma M = 2.5N \cdot mm \). It is obviously that \( \Sigma M > M_{\text{max}} \), so a conclusion can be obtained that the inflatable structure can deploy smoothly.

For filmed cavity structures, stress state analysis is conducted to one of the elements on the thin-wall tube and the spatial stress matrix is obtained as:
Due to the extremely small differential pressure between the inside of the cavity and the outside, its radial stress $\sigma_r$ can be neglected compared to axial stress $\sigma_n$ and circumferential stress $\sigma_\tau$, with

$$\begin{align*}
\sigma_r &= \sigma_z = 0 \\
\sigma_n &= \sigma_x = \frac{pr}{t} \\
\sigma_\tau &= \sigma_y = \frac{pr}{2t}
\end{align*}$$

In addition, as no torsion moment influences the thin-wall tube, there is no shear stress. Therefore, the spatial stress matrix can be simplified as:

$$\begin{bmatrix}
pr & 0 \\
\frac{pr}{t} & 0 \\
0 & \frac{pr}{2t}
\end{bmatrix}$$

According to the fourth strength theory, the stress of tube wall can be calculated as $\sqrt{3}MPa$, which is far less than the allowable stress of material. Therefore, the strength of the material is enough.

By using of dates which have been calculated, the simulation can be done with the help of LS-DYNA software. The stress nephograms of the inflatable structure during deploying are calculated in the post processing software LS-PREPOST as shown in Fig. 6.

Fig. 6 Inflatable deployable structure stress nephogram
As shown in Fig. 6, with the designed structure deploying smoothly and steadily, the stress on the thin film almost has a uniform distribution.

**Analysis of Deployment Trajectories.** For inflatable and deployable designation, the trajectories of its integral structure are always not regular. Once there is severe vibration or uncontrollable shape change during expanding, wrinkling is easy to appear, which may even lead to serious tearing in the connecting part between the films. However, such tearing is not allowed to happen as it will cause a deployment failure by air leakage. Smooth and steady deployment can avoid the above problems. Specific to the structure designed in this paper, 20 points along the edge are selected for motion trajectories analysis. In Fig. 7, these trajectories are plotted in a 3D graph in MATLAB. It is obviously that all the moving curves are parallel so that the inflating and deploying process is smooth and steady.

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<th>Fig. 7 Deployment trajectories</th>
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Without loss of generality, one trajectory of the points is chosen to analyze. Here the curve fitting toolbox in MATLAB is used to fit the curves \( x(t) \), \( y(t) \) and \( z(t) \) related to time \( t \), as shown in Fig. 8.

<table>
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<tr>
<th>Fig. 8 The fit curve of ( x(t) ), ( y(t) ) and ( z(t) ) related to time ( t )</th>
</tr>
</thead>
</table>

When the fitting model is Fourier, the results are as following:

\[
\begin{align*}
    x(t) &= a_0 + a_1 \cos(wt) + b_1 \sin(wt) + a_2 \cos(2wt) + b_2 \sin(2wt) + a_3 \cos(3wt) + b_3 \sin(3wt) \\
        &\quad + a_4 \cos(4wt) + b_4 \sin(4wt) \\
    y(t) &= a_0 + a_1 \cos(wt) + b_1 \sin(wt) + a_2 \cos(2wt) + b_2 \sin(2wt) + a_3 \cos(3wt) + b_3 \sin(3wt) \\
        &\quad + a_4 \cos(4wt) + b_4 \sin(4wt) \\
    z(t) &= a_0 + a_1 \cos(wt) + b_1 \sin(wt) + a_2 \cos(2wt) + b_2 \sin(2wt) + a_3 \cos(3wt) + b_3 \sin(3wt) \\
        &\quad + a_4 \cos(4wt) + b_4 \sin(4wt)
\end{align*}
\]

(8)

The parameters values in the Eq. (8) are shown in Table 2 and Table 3.
Table 2 The parameters in Eq. 8

<table>
<thead>
<tr>
<th>$a_0$</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$a_3$</th>
<th>$a_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x(t)$</td>
<td>-3.249e+011</td>
<td>5.16e+011</td>
<td>-2.524e+011</td>
<td>6.948e+010</td>
</tr>
<tr>
<td>$y(t)$</td>
<td>-236.2</td>
<td>147</td>
<td>197.6</td>
<td>-94.12</td>
</tr>
<tr>
<td>$z(t)$</td>
<td>18.89</td>
<td>-36.12</td>
<td>61.07</td>
<td>10.64</td>
</tr>
</tbody>
</table>

Table 3 The parameters in Eq. 8

<table>
<thead>
<tr>
<th>$b_1$</th>
<th>$b_2$</th>
<th>$b_3$</th>
<th>$b_4$</th>
<th>$w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x(t)$</td>
<td>6.492e+010</td>
<td>-6.454e+010</td>
<td>2.739e+010</td>
<td>-4.501e+009</td>
</tr>
<tr>
<td>$y(t)$</td>
<td>404.6</td>
<td>-174.5</td>
<td>-44.89</td>
<td>20.71</td>
</tr>
<tr>
<td>$z(t)$</td>
<td>113.5</td>
<td>9.316</td>
<td>-46.99</td>
<td>1.943</td>
</tr>
</tbody>
</table>

Same as according to the above process, 10 trajectories are analyzed. Their fitting confidence coefficients (R-Square) are all approaching 1, which shows that this fitting method is suitable to the deployment curve. So the structures deployment trajectories can be described as the Eq. 8.

**Prototype Deployment and Primary Experiment**

An inflatable deployment structure is designed according to the results of the above chapters. Because the film surface should be smooth and easy to expand, plastic film is adopted for this structure. The inflation process of the structure is conducted by axial flow fan. The experiment can verify whether it can deploy successfully, and the working principle of the structure is as follows. The axial flow fan works from the very first and the outside air will be pumped into film tubes. The initial state of film is folding as shown in Fig.9 (a). As the aeration process smoothly goes on, the film will gradually deploy itself from the folding state under the pressure of gas. The final deployed status is shown as Fig. 9(c). Prototype deployment process is shown in Fig.9.

![Fig.9 The prototype deployment](a) (b) (c)

It is shown that the prototype model deployment is a smooth process through the experiment. When the internal pressure of the film tube continues increasing, the film surface fold is disappearing. The whole process of deployment is steady and there is no large deformation on the surface of film.

**Conclusion**

This paper designs an inflatable deployment structure based on the eclosion process of butterflies. The inflation pressure is calculated in order to obtain the resultant moment at the folding point of the structure, which proves that the structure can deploy under this inflation pressure. With the analysis of the LS-DYNA simulation results, it is found that such structure has a simple method of deployment and a steady motion process. The experimental results of the prototype show that this kind of inflation deployment can reduce the probability of failure during the deploying process and the reliability of the structures can be substantially improved. Inflatable deployment structure’s contraction ratio is quite attractive through analyzing the fold and unfolds states based on the prototype. This deployable
structure and simulation method will provide a guidance and reference for future design of inflatable structures. Our future interest will be to use this deployment mechanism for practical tasks. Inflation structure’s superior performance makes it a good candidate in military, aerospace and other correlation domain. So our working emphasis is to take advantages of inflatable deployment structures as much as possible so that it will meet a variety of tasks’ demands.

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