Bio-inspired Design of an Inflatable Deployable Structure

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Abstract—The biomimetic principle applied in the deployable structure design process has important significances in engineering reality. Principle in nature provides numerous design solutions for innovative deployable structures. Meanwhile, it has initiated a new area for biomimetic research. In this paper, the mechanism of butterfly ecolision deploy process is introduced. According to the butterfly wings ecolision development process, a type of deployable structure is proposed. Optimization design is put forward according to problem which is finding on the early-developed prototype. The optimized results prompt a new deployable structure with much better mechanical characteristics and structural performance. And then, an inflatable deployable structure prototype is developed. Finally, experiment successfully demonstrates the bio-inspired principle of above proposed inflatable deployable structure.

Keywords—deployable; elosion; inflatable; optimization

I. INTRODUCTION

Deployable structures, as an important kind of space structure, have been widely used in a variety of spacecraft antennas, solar panels, solar sails, infrastructures and so on[1-6]. Under the size and cost limitations of launch vehicle’s transportation system, deployable structure usually requires large contraction ratio and high reliability. How to make the designed structure meet the ideal requirements are still great challenges to their research and development process[7-8].

Biomimicry and adaptations from nature are the exercises in learning from nature and applying to man-made systems[9]. During the recent years, the advancement of bionics provides some new solutions to develop various deployable structures. Yoon et al designed the UAV wing inspired by the insect’s foldable wing[10]. Sun et al developed a two-wing deployable structure like butterfly wing[11]. Katsumata et al had researched on the dynamic behavior of inflatable booms in zigzag[12]. Vincent provided a general review of the nature developable structures[13]. Focatiis and Guest researched on the leaf-type deployable membranes[14]. Kishimoto et al also research on the nature original deployable structures[15]. There are still other new design solutions for a deployable structure with humankind’s increasing knowledge about the nature. Successful design a bio-inspired structure needs extensive and in-depth investigation on the original bio-structure. Experiences, simulation, and experiments can be used in bio-inspired system developments.

The rest of this paper is organized as flow. Firstly, the research on butterfly-inspired deployable principle is introduced. According to the butterfly wings ecolision development process, a new type of deployable structure is proposed. And then, the structure is optimized and analyzed in detail. Finally, a prototype of the proposed inflatable structure is developed and tested.

II. THE RESEARCH OF BIONIC DEPLOYMENT STRUCTURE

There is an overwhelming abundance of insects in nature and the insect’s ecolision development has a unique characteristic. For insects’ ecolision, the most complete and representative case is the lepidoptera insect metamorphosis. Lepidoptera insects’ individual developments are accompanied with metamorphosis process. Insects of this kind are all complete metamorphosis insects, because they go through four different full developmental stages of life, that is, the embryo stage, the larva stage, the pupa stage, and the imago stage which are shown in Fig. 1. In the process of ecolision between pupa stage and imago stage, it shows that the wings change from firstly small to bigger and then soft to harden. The body surface area of pupae will have a great difference with that of adult insect which has been formed during the ecolision. This is an new finding and this nature process can be used for bionic space deployable structure’s design. Based on the comparative study of these insects ecolision, a phenomenon was found that the butterfly ecolision process was very representative. Thus, according to the characteristics of the butterfly ecolision, a series of research on the deployable structure has been carried out in the rest of this paper.

A. The Ecolision and Development Process of Butterfly

Previous study has found that nervures of butterflies’ scaly wings play an irreplaceable role in the development process. At the beginning of the ecolision development, the adult wings are very delicate and crinkled. With a lot of lymph started flowing to nervures, the wings can spread quickly and harden. According to the research, the butterfly ecolision development is divided into two phases. The first phase is inside pupae development. The formation of nervures which is in the butterfly wings is completed in this process. Along with the time the nervures are clearly visible under a microscope through dissection which is
shown in Fig. 2. The second phase is outside pupae development. This process spends more time compared with the first process. With the tissue fluid inflowing into the wings through nervures, the wings expend gradually and the area of the wings become bigger and bigger which is shown in Fig. 3. It is the two processes that provide biological principles for bionic deployable structure’s design.

**B. The Concept Design of a Deployable Structure**

As the two layers patagiums are pressed to the nervures and the nervures are cavity structure which is shown in Fig 4, the model is clear. According to the structural characteristics of the Idea leonore, we built the 3D model with solidworks software. After the butterfly emerges from pupae, a lot of lymph started flowing to veins and the wings spread gradually from a small volume. It is can be concluded that the fluid which is in butterfly play the role of power source. Therefore, the designed structure’s power can be selected for fluid according to this principle. But for deployable structure, one of the key issues is mass. The ideal deployment structure has some excellent characters such as light weight and high efficiency. So the power source could select a fluid such as gas which has lower weight. Through researching the key issue of weight, the nature air should be a good choice. In order to simulate the inflatable deployment process, a simulation model is established for the coiled state. The dark part is corresponding to the butterfly’s veins. This part can provide power and support for the deployable structure. The other part is all films which is used for connection between the veins. The final inflatable simulation model of a two-wing structure is shown in Fig. 5.

![Fig. 2 The changes of the nervures in the pupa.](image1)

![Fig. 3 The changes of the area as the tissue fluid flow into the wings in the second phase.](image2)

![Fig. 4 The structure of the wing.](image3)

![Fig. 5 Inflatable simulation model of a two-wing structure.](image4)

After the simulation of the structure, it is proved that such structure can deploy successfully from coiling to expanding by inflation. And inflation is the only workload during the deploying process without any requirement for electronic design. The deployed structure has a bigger stowed volume ratio and a two times longer size than its initial state. This structure adopts plastic film which can save much fabricating cost.

By considering the practical applications of some antennas are all rotundity and presenting with a whole piece of plane
state. So the array operation can be taken. A same structure is added along the circumferential direction, as shown in Fig. 6.

![Fig. 6 Configuration of the proposed deployable structure.](image)

### III. OPTIMIZATION DESIGN AND DYNAMIC SIMULATION OF BIONIC STRUCTURE

The complexity of the structure is an important indicator which is evaluating inflatable development structure’s practicality. The established structure is relatively complex in the previous section. Although the model deployment process has been validated by simulation analysis, the structure is relatively complex which leads to stresses concentrating at certain points. The structure has too many corners and forks so that inflation process may have some problems such as leaks and wrinkles. In the practical engineering application, structure is relatively simple and easy to expand, so the structure adopts topology optimization in order to meet demand.

#### A. Topology Optimization of inflatable deployment structure

For this structure, the connection of the film cannot reduce. Therefore, a part of the need to simplify is only the structure of skeleton which is corresponding to the black parts in Fig. 6. This idea is equivalent to the simplification of the veins in butterfly wings. The numbers of veins should reduce as much as possible, but it must meet the requirements under the certain condition. The result of topology optimization is shown in Fig. 7.

![Fig. 7 The result of the logy optimization of the model.](image)

According to Fig. 7, there are two colors in this picture. The red parts need to keep. The blue parts can remove from the structure. In order to ensure the optimized structure stiffness, two inflatable circle tubes are added in the outer ring and inner ring. Therefore, the primary configuration of simplified structure is established according to the results of the optimization, as shown in Fig. 8.

![Fig. 8 The primary configuration of the model.](image)

The virtual prototype model is designed as shown in Fig. 9 by considering practical application of inflatable structures. The bottom of this structure is arranged four inflatable tubes which has important supporting role.

![Fig. 9 The virtual prototype model is designed.](image)

#### B. Dynamics Simulation of Inflatable Deployment Structure

With the help of LS-DYNA software, we can simulate the process of the inflatable deployment structure. The stress graph of the inflatable structure during deploying are calculated in the post processing software LS-PREPOST as shown in Fig. 10. It can be seen from Fig. 10 that, with the designed structure deploying smoothly and steadily, the stress on the thin film almost has a uniform distribution.

![Fig. 10 Stress graph of the inflatable structure during deploying.](image)
IV. ANALYSIS OF THE STRUCTURE CHARACTERISTICS

After the establishment of the virtual prototype model by using topology optimization method, the inflatable tube has been reduced more than before. Therefore, the structure must carry out a series of finite element analysis in order to investigate the structure’s stiffness and its dynamic characteristics.

A. Stiffness Analysis of Structure

After the structure deployment, it is necessary to analyze deformation degree by using the linear statics analysis. Under static load, the structure is in static equilibrium position. At this time, the structure must be fully constraint. The structure has nothing to do with mass without thought of inertia. But in many cases, if the load cycle is much greater than structural natural vibration period, the inertia effect of the structure can be ignored. The bottom of structure is fixed. The largest deformation should be examined under the weight. The results of the analysis are shown in Fig. 11.

B. Modal Analysis of the Structure

Modal analysis is one of the most simple dynamics analyses, but it has very extensive application value. The advantage of modal analysis is that the structure’s design could avoid resonance or vibration at a particular frequency. According to analysis result, engineer can recognize the response of structure which is under different types of dynamic loads. It can help to estimate the solution control parameters in other dynamic analysis.

The equation of motion in undamped modal analysis can be written as,

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{0}$$

(1)

Sine displacement functions of harmonic vibration is given as follow,

$$\left(\mathbf{K} - \omega^2 \mathbf{M}\right)\mathbf{x} = \mathbf{0}$$

(2)

Substitute Eq.(2) into Eq.(1), we can get the relationship as follow.

$$\left(\mathbf{K} - \omega^2 \mathbf{M}\right)\mathbf{x} = \mathbf{0}$$

(3)

The eigenvalue of Eq.(2)is $\omega_i^2$ and the natural frequency of vibration is $\omega_i / 2\pi$. The known eigenvalue is $\omega_i$, so the corresponding eigenvector is $\mathbf{x}_i$. This eigenvector is mode of vibration which is corresponding to natural frequency of vibration. The structure of modal analysis result as shown in Fig. 12.

The modal analysis result has shown that its fundamental frequency is 15Hz. The second to five order modal shapes are also shown in Fig. 13 and Table 1.
C. Harmonic Response Analysis of the Structure

The load of Harmonic response analysis is a harmonic load which is changing with sinusoidal time function. This type of load can be described by used of the frequency and amplitude. Harmonic response analysis can calculate the structural response which is caused by a series of load with different frequency and amplitude at the same time. This is the so-called frequency scanning analysis. The structure of harmonic response analysis result as shown in Fig. 14.

The harmonic response analysis can determine the structure’s steady state response under the sine load. According to the analysis result, when the frequency is 450 Hz, the structure will have maximum amplitude and the maximum deformation is 0.001 mm. It can be concluded that the structure has good mechanical properties through the above analysis, and this structure can satisfy with the design requirements.

V. Prototype Deployment and Primary Experiment

In order to validate the result of the simulation and achieve the structure’s deployment state, a prototype model is made necessarily. This structure mainly includes two key parts. The first part is power source of structure. The second part is the structure characteristics and the material’s selection.

Power of the structure is comes from the gas. The external gas continuous injects into gas tube and the structure can deploy from folding state to the final state.

Due to the structure need to be slowly spread, the inflation rate should be controlled effectively. Gas charging device must be selected properly so that the stability of structural deployment process could be ensured. The economy of electric gas charging device maybe slightly worse compared with the manual gas charging device, but it can guarantee inflation rate and realize continuous inflation process. In order to ensure the deployment process could be uniformity and stability, the better chance is electric gas charging device.

This structure is made of plastic film, because the film surface is smooth and easy to expand. Connection between the films parts can use of sealing adhesive, so the air leakage will be prevented effectively. Inflation inlet of this structure adopts the following form, as shown in Fig. 15.

The structure consists of three film layers. The middle of film layer is bonding with the above of film layer, but it is not the entire surface adhesive. One end is inflation inlet which with white marks, another end can be sealed. When the structure completes inflation process, inflation inlet can realize automatic sealing and prevent air leakage phenomenon, as shown in Fig. 16.
The experiment of deployable structure can be carried out after prototype is making completion. Deployment process of this structure is shown in Fig. 17. The structure main parameters after deployment are shown in Table 2.

| Specifications | Details |
|----------------|---------|
| Diameter       | 0.5m    |
| Height         | 0.3m    |
| Mass           | 300g    |

The experimental process of inflatable deployment structure can be divided into three steps. In the first step, a protective layer is packed at the inflatable deployment structure outside. It can prevent the structure internal temperature rapid fluctuations. The protective layer can avoid structure’s damage, so the structure can deploy smoothly. In the second step, electric gas charging device connect to the inflation inlet of structure, the sealing performance of interface should be verified. In the third step, the electric gas charging device starts to work. The inflation pressure should be observed and pay attention to deployment process. When the structure deploy totally, it can stop inflation.

![Fig. 17 The deployment process of the model.](image)

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.

VI. CONCLUSION

Based on the butterfly wing’s structure, this paper designs a prototype of inflatable deployable structure. Considering that the surface should be easy to deploy and fold, plastic film is suitable for this membrane structure. In order to avoid leakage, the connection part is sealed by sealant. The inflation process of the structure is conducted by axial flow fan. The complexity of inflatable developable structure is an important index which evaluates practicability of the structure. The structure is relatively complex as for the early-developed prototype. So this paper optimizes the complexity of the structure and presents an improved prototype which has better structure configuration. The improved prototype’s model is simpler than the previous structure. It has smoothly deployed process and better feasibility.

In the next step, our intention will be to use this deployment mechanism for practical tasks. The material of the structure still requires investigation so that it has enough strength. The deployable structure and simulation method in this paper will provide some references for future design of inflatable structures.

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