New Deployable Membrane Structure Models Inspired by Morphological Changes in Nature

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Some characteristics of morphological changes in nature are discussed and morphological changes in space structure systems are investigated. Essentially space structure systems change their forms and functions, since they must be initially stowed due to spatial constraints of transportation systems, and deployed in their designed orbits. Recently various concepts of membrane structures are proposed for future large space systems, since they can be compactly stowed, and can easily realize space structures with large area. In their developments, it is a major important issue to ensure the reliability of their deployment processes. From the viewpoint of deployment processes, various morphological changes of some plants, insects, and animals are investigated. The efficient characteristics in their morphological changes such as high redundancy, sequential deployment, utilization of gravity forces, and so on are introduced. A new concept of deployable membrane structure models derived especially from the observation of insects' metamorphosis including eclosion of butterflies, dragonflies, cicadas, and so on is proposed. Numerical results of its deployment behavior are also shown.

Nomenclature

ϕ	=	diameter of an inflatable tube
R_s	=	cylinder radius of an central satellite bus
R_m	=	radius of an inscribed circle of hexagonal membrane
$\tilde{\Gamma}$	=	modified stiffness matrix of a membrane element
E	=	Young's modulus of membrane
ν	=	Poisson ratio of membrane
P_1, V_1, m_1, T_1	=	pressure, volume, mass and temperature of a low pressure tube element, respectively
P_2, V_2, m_2, T_2	=	pressure, volume, mass and temperature of a high pressure tube element, respectively
A	=	sectional area of an inflatable tube
C	=	orifice coefficient of working gas
κ	=	specific heat ratio

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I. Introduction

Various concepts of membrane structure systems have been proposed for large space structures such as space antennas, solar sails, solar power satellites, and so on^{1,2}. Such systems are compactly stowed, and can easily realize space structures with large area. They are effective for space transportation systems having spatial and weight limitation. Membranes are tension members, and usually corresponding compression members are necessary. A representative example of such systems is the square solar sail recently developed especially in the U.S.^{3,4}. For larger space structure systems over 100m-scale, usage of centrifugal forces and gravity forces seems to be efficient instead of usage of compression members⁵. These membrane structure systems are naturally deployable structure systems, which can easily cover the necessity of space systems in near future. It is a major important issue to ensure the reliability of their deployment processes.

In order to look for a new possibility of deployable membrane structure systems, we focus on morphological changes in nature. Although current shapes and functions of living things in nature are not always fit for engineering purposes, they show high possibility to adapt to changes of environments^{6,7}. One of design principle for biological structural systems is using tensile materials, which reduce total weight⁸. Various morphological changes in plants, insects, and animals are observed. They show some efficient characteristics for deployable structures such as high packaging efficiency, high redundancy, sequential deployment, usage of gravity forces, and so on. Based on these characteristics, we propose a new concept of deployable membrane structure models especially inspired by eclosion processes of insects: they are membrane structures, which embed inflatable tubes. Some examples are introduced for future large planar space membrane structures. Numerical analysis of deployment behavior of a representative model for spinning solar sail is also shown.

II. Morphological Changes in Nature

This section treats various morphological changes widely seen in nature. Especially we focus on deployment structures, which involve flowers and leaves in plants, wings of insects and animals. As shown in Table 1, some examples of deployable structures in nature are classified into four groups according to the following two points. One is whether the deployment process is reversible. And the other is whether the deployment process is due to remarkable volume increase.

Table 1 Morphological Changes in Nature

	With remarkable volume increase	
	Yes	No
Deployment only	Case A: Bloom of dandelion Development of new leaves	Case B: Bloom of morning glory Eclosion of insects
Both deployment and storage	Case C: -	Case D: Bloom of bindweed Open-close movement of sensitive or insectivorous plants Flap-stowage of beetle's hind wings Flap-stowage of bat's wings

A. Flowers and Leaves (Plants)

Morphological changes in plants including deployment of flowers and leaves are introduced. There are various types of leaf arrangements, flower crowns, inflorescences. At first, some examples of new leaves are shown in Fig.1. This figure provides that all leaves are initially scale-down and stowed in folded or wound configuration. They gradually grow due to scale-up and deployment processes. Figure 2 demonstrates development of leaves of a legume plant. The total number and arrangement of leaflets are kept through the development, however the size and orientation are gradually changed. These morphological changes are classified into case A in Table 1, because the processes are not reversible and need remarkable volume increase. In addition to this development of leaves, morphological changes in leaves include open-close movement of sensitive or insectivorous plants. The movement is categorized into case D in Table 1.

(a) foliage plant
(b) bramble
(c) maple
(d) wolfsbane

Fig. 1 Some examples of new leaves.

Fig. 2 Development of bipinnately compound leaves of a legume plant.

Next, bloom of flowers is discussed. Figure 3 shows bloom of ladies' tresses. In this case, simultaneous circumferential and vertical bloom forms its unique spiral structure. Bloom of various types of flowers is illustrated in Fig.4. A flower of dandelion(a) or sunflower(b) is composed of tubular and ligulate corolla and deploy their folded petals sequentially. Deployment of dandelion is due to growth of corolla, and it is categorized into case A. Broad petals of poppy are crumpled in its calyx(Fig.4(c)).

Flowers stated above are composed of several corolla or petals. Figure 5 shows bloom of morning glory and

Visual data provided by Prof. Yamashita of ISAS/JAXA

Fig.3 Bloom of Ladies' tresses (*Spiranthes sinensis* var. *amoena*).

Fig.4 Bloom of various types of flowers.

Fig. 5 Bloom and helically-wound buds of morning glory and bindweed (infundibular corolla).

bindweed, which flowers are composed of one infundibular corolla. However, morning glory bloom in morning only once, bindweed bloom in the daytime and stowed in the nighttime for a few days. The bloom process of the former is categorized into case B and that of the latter is categorized into case D. Petals of buds of both flowers are wound shown in Fig.5 (c). The petal of morning glory is wound more helically than that of bindweed due to its repeated open-close movements. This feature remains after deployment on the same reason.

B. Insects

Morphological changes in insects are introduced. Insects need several ecdysis processes, since they have external skeleton. Figure 6 illustrates pupation process of last instar larva of a papilionid butterfly. Morphological changes shown in this section proceed with time from left to right. The shape after the process is very different from that before. Ecdysis and eclosion processes are basically categorized into case B. In addition, morphological changes in insects involve flap-stwrage of beetles' hind wings, which categorized into case D. We give a detailed description of eclosion processes below.

Fig. 6 Pupation process of last instar larva of papilionid (*Papilio machaon*).

Fig.7 Eclosion process of cabbage butterfly (*Pieris rapae*).

Eclosion of a cabbage butterfly is shown in Fig.7. Influx of body fluid into branching veins induces deployment of wings. Figure 8 demonstrate eclosion of a nymphalid butterfly, which pupa is hanging head down. In this case, he alters his position during eclosion process.

Fig.8 Eclosion process of nymphalid (*Sasakia charonda*).

Butterflies stated above are complete metamorphosis insects. Figure 9 shows an eclosion process of a dragonfly *Anax parthenope Julius*, which is an incomplete metamorphosis insect. Four thin membrane wings are stowed in four sheaths on the back of a larva of a dragonfly. A wing consists of thin membrane with many branching veins, and deploys to about forty-fold from its original area. It proves that influx of body fluid into branching veins can expand stowed wings. At last an eclosion process is completed by changing colors of the dragonfly which indicates rigidization of the membranes, veins, and body. Another type of dragonflies' eclosion is shown in Fig.10. In this case, longitudinal axis of wings is perpendicular to the direction of gravity forces.

We point out the following characteristics of the eclosion processes from the viewpoint of structural engineering.

Fig.9 Eclosion process of flying dragon (*Anax parthenope Julius*).

Fig. 10 Eclosion process of Gomphidae (*Davidius nanus*).

1) Insects' wings are combined structure systems with thin membranes and inflatable veins. And their membranes, veins, and bodies are rigidized after deployment processes.

2) Deployment of a membrane is caused by inflation of branching veins due to influx of body fluid.

3) All body fluid begin to flow from chest of an insect. And it spreads into every edge of wings due to hierarchically branching veins. Diameters of veins become smaller from upper to lower.

4) Dragonflies could use gravity assist in deployment of their membranes, since they change their orientation of body to adjust their directions of expansion of wings to gravity forces.

5) We examine details of a hind wing inside a sheath of a last instar larva of a dragonfly *Sympetrum eroticum* under microscope. They show that their membranes and veins are folded hierarchically in their sheaths. Hierarchical folding patterns are naturally generated since growth of their membranes is faster than that of their sheaths.

C. Bats (Animals)

Lastly we just refer to flaps of bats' wings shown in Fig. 11. They can open and close their membrane wings quickly.

Fig. 11 Flaps of bat's wings.

Fig.16 Example models of proposed membrane structures.

B. New Deployable Structures Inspired by Insects' Eclosion

1. New Concepts of Deployable Membrane Structures

Considering the characteristics of insects' eclosion among morphological changes in nature stated above, we propose new deployable membrane structure systems, which embed branching inflatable tubes rigidized after their deployment. All inflatable tubes begin from a central satellite bus.

Figure 16 shows two example models of such systems. Heavy lines indicate embedded inflatable tubes. In these cases, inflatable tubes are attached to folding lines of a hexagonal membrane. The both folding patterns are proposed for deployment using centrifugal forces applied to spinning solar sail spacecrafts¹². We describe characteristics of proposed membrane structure systems in the following.

- 1) This system needs one tank and device for supplying gas, since all inflatable tubes come from central satellite.
- 2) We can design geometrical patterns of inflatable tubes without relation to folding patterns. Using branching tubes make deployment process of membranes more smoothly, since number of tubes per an area comes to be constant. Figure 17 shows some examples of geometrical patterns of tubes, which include fractal geometry. These patterns are easily extended to various sizes and shapes of membranes.
- 3) This system is easily used in combination with other deployable methods such as using deployable masts, centrifugal forces, and so on.
- 4) We have possibility of controlling deployment processes, since deployment forces due to centrifugal forces are stronger in outer area than inner area, and those due to inflatable tubes are the contrary.
- 5) Rigidized inflatable tubes provide stiffness and strength to membrane structures. We can provide adequate stiffness distribution of membrane structures by designing branching patterns or distribution of diameters of inflatable tubes (Fig. 17).

Fig. 17 Three examples of branching patterns of inflatable tubes on hexagonal membrane.

2. Numerical Analysis of a Hexagonal Membrane Model

In this study, we use one kind of nonlinear elasto-dynamic analysis code developed for numerical analysis of membrane or cable structures^{13,14}. This code is characterized by modified stiffness matrix, which means that stiffness becomes 0 or drastically reduced under compression forces. Modified stiffness matrix $\tilde{\mathbf{I}}$ is expressed the following equations.

$$\tilde{\mathbf{I}} = \frac{E}{1 - a_1 a_2 \nu^2} \begin{bmatrix} a_1 & a_1 a_2 \nu \\ a_1 a_2 \nu & a_2 \end{bmatrix}$$

$$\begin{cases} \text{taut element} & : (a_1, a_2) = (1, 1) \\ \text{wrinkled element} & : (a_1, a_2) = (\eta_1, 1) \\ \text{slack element} & : (a_1, a_2) = (\eta_1, \eta_2) \end{cases}$$

,where η_1 and η_2 are arbitrary constants greater or equal 0. In this study, both constants are set to 0.

Moreover, contact between membrane and satellite body is also considered. Gas flow within a tube is assumed as one dimensional compressive stationary isentropic flow expressed by the following equation.

$$\dot{m} = CA \sqrt{\frac{2\kappa}{\kappa - 1} \frac{P_1 m_1}{V_1} \left(\left(\frac{P_2}{P_1} \right)^{\frac{2}{\kappa}} - \left(\frac{P_2}{P_1} \right)^{1 + \frac{1}{\kappa}} \right)}$$

Representative constant data are shown in Table 2 and a model for numerical analysis is shown in Fig. 18.

Deployment behavior of hexagonal membrane models is shown in figure 19. Figure 19 (a) shows the case of deployment without injection and figure 19(b) shows the case with injection. From the comparison between two cases, the case of deployment with injection shows smooth deployment without local deformation. But there appears forced deformation along tube elements. Almost complete deployment accomplishes at 6.0 second. In the case of deployment without injection

Table 2 Constant Data

membrane material	polyimide
Young modulus	6.963 GPa
Poisson ratio	0.3
membrane thickness	7.5 μm
atmospheric pressure	1.0×10^{-5} Pa
working gas pressure	1.0×10^{-3} Pa

Fig. 18 Analyzed membrane model.

Fig. 19 Deployment behavior of hexagonal models.

Fig.20 Deployment Rate Comparison.

shown in fig.19(a), local deformation appears and there are many elements with high strain energy density.

Deployment behavior shown in figure 19 is quantitatively evaluated in figure 20, which shows the time history of the rate of deployment area. Overall deployment behaviors with injection and without injection are well presented, and local vibratory behavior is also clarified.

IV. Conclusion

Deployable structure systems in nature and in space systems are reviewed from the viewpoint of morphological changes. The observation of morphological changes in nature, which include plants, insects, and animals, provides some efficient mechanisms and characteristics to develop deployable structure systems in space systems. Especially we propose a new concept of deployable membrane structure models: they are membrane structures, which embed inflatable tubes. Numerical results of deployment behavior of a representative model indicate its efficiency for smooth deployment process

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