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Design & Analysis a Flytrap Robot using Bi-stable Composite

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***Abstract*— This paper presents a second prototype of the flytrap robot which mimics the fast snap-through motion of the Venus flytrap, the previous version of the robot. This second prototype employs a new type of unsymmetrically laminated carbon fiber reinforced prepreg (CFRP) structure which has two different curvatures, and an SMA spring actuator. To estimate the force of snap-through the structure, a linear beam bending model is introduced and a force-displacement experiment is demonstrated. Based on the numerical and experimental results, the flytrap robot can be closed rapidly and opened for re-load. The closure time is about 100ms.**

I. Introduction

THE Venus flytrap (Dionaea muscipula) is an insectivorous plant which shows one of the fastest motion in the plant world. The rapid trapping motion is a typical characteristic of the Venus flytrap. Recently, the principle of the fast closing movement of the leaves was the first described by Mahadevan from a mechanical-structure point of view [1]. He focused on the post-stimulation mechanical aspects of the Venus flytrap closure having snap-buckling instability in a doubly-curved leaf and employing two principles of trap snapping. The previous study of a flytrap robot presented the similarity between the bi-stability of the doubly-curved leaf of the Venus flytrap and the bi-stability of the unsymmetric laminate CFRP structure as shown in Fig. 2 [2].

In the study of composite materials, unsymmetric bi-stable composite structures have been studied extensively. The bi-stability is due to the difference of the thermal expansion between two different orientations of fibers in composite laminar layers. For this reason, the shapes of cured composite laminate structures are observed to have both cylindrical curvatures but different curvature axis configurations like Fig. 3. In particular, Hyer et al. summarized the bi-stability of unsymmetric carbon fiber reinforced laminates and Cho et al. studied the slippage effects on the bi-stable curvatures of unsymmetric composite laminates after curing [3]-[6]. Based on these results about bi-stable structures, a study is currently in progress about smart structures or morphing structures with embedded actuators [7]-[10]. Hyer et al. developed a theory on the before and after configurations via snap-through of bi-stable composite structures [9]. Also his group conducted experiments about the snap-through characteristic of bi-stable composite structures. Furthermore, a follow-up study investigated the embedding shape memory alloy (SMA) wires , which is adopted as an actuator to induce the snap-through of unsymmetric composite laminates [10].

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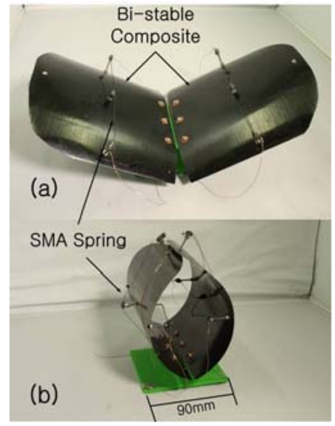

Fig. 1. Flytrap robot with SMA spring actuator. (a) is opened state and (b) is closed state.

The previous flytrap robot was developed based on the bi-stability of composite structure and it used a SMA spring actuator for snap-through [2]. Though the robot performed the closure motion similar to the flytrap plant, it did not show the open motion, which needs large deformation. Also, the structure of the robot was not analyzed fully.

In this paper, we set a design target, which is, to mimic the leaf of the Venus flytrap based on statistical analysis, and try to duplicate the open state of the flytrap robot. First, we introduce a simple theory of segmented linear beam bending. Then an experiment of force-deformation with unsymmetric bi-stable CFRP structure is conducted to compare the results with numerical analysis results. From these numerical and experimental results, the required force of the SMA actuator to duplicate the snap-through of the flytrap robot leaf was determined to be 5N.

In the following section, the design part of the robot considers one, the curvature of the bi-stable CFRP structure and two, the attachment of actuators for open and close motions. For these design considerations, two manufacturing processes are described. One is about the bi-stable laminated CFRP structure, as a leaf of the flytrap robot, which has two different curvature sizes and the other is about the SMA spring actuator which generates 2.5N force. The flytrap robot, which is shown in Fig. 1, has a closure speed of about 100ms like that of the flytrap plant and can repeat the open-closure movement.

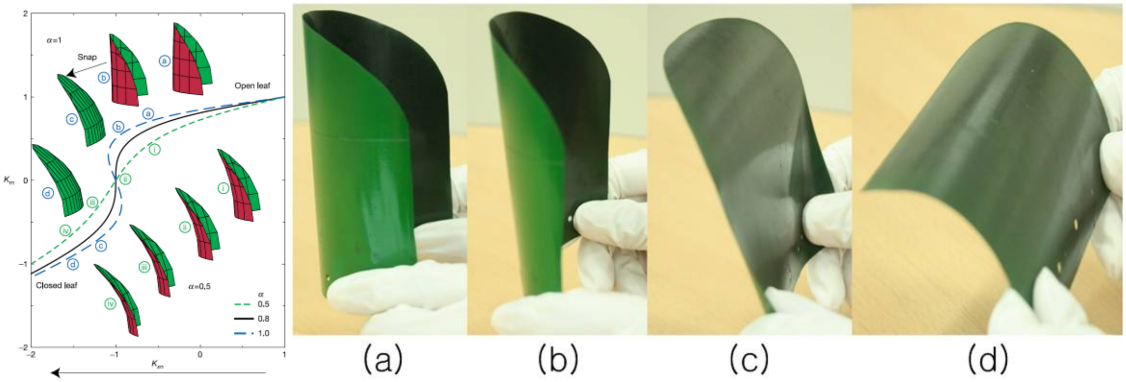

Fig. 2. The flytrap's smooth-snapping transition in leaf closure diagram (far left figure) [1]. Applying bending moment by fingers, CFRP composite snap-through progress sequence from (a) to (d) .Snap-through occurs between (b) to (c) [2].

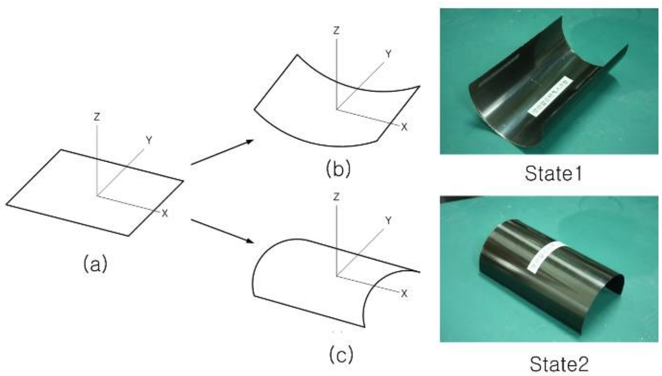

Fig. 3. [90/0] Bi-stable composite structure reference coordinates.

II. Design

In this section, we develop an advanced design of the flytrap robot which can perform much like the real flytrap. Also this advanced design complements the problems in the previous flytrap robot.

A. *A Bi-stable Structure for Different Curvature Sizes*

In the previous investigation about the flytrap robot, bi-stable CFRP structures from curing in the flat plate are used as the leaf of the robot. In this case, the structure has same curvature size configurations at the open and close state. But the flytrap has small curvature in opened leaf and big curvature in closed leaf for trapping easily. Therefore, we clamped the entire edge of one side of the structure to suppress a curvature size of one configuration and flatten it so that it takes similarly the open shape of a real flytrap leaf. However, this result in a problem over time that the open state curvature diminished due to clamp force and finally clamped structure cannot stand the open state.

To get one state is curved shape but the other state is almost flat so that it can snap-through leaf closure efficiently in flytrap robot, we make a hypothesis. The hypothesis is that an initially curved cured bi-stable structure will produce different curvature shapes at state 1 and state 2. To verify this, an experiment about initially curved curing unsymmetric CFRP on the steel jig plate is conducted.

The test curvatures of the steel jig plate are $8.33m^{-1}$ and $6.66\ m^{-1}$. The jig plate was subjected to heat treatment to prevent deformation due to the heat process. The CFRP laminar layup order is that 0° oriented laminar is at the bottom and 90° oriented laminar is at the top. The experimental result is described in Fig 4. In Fig. 4, (a) When the CFRP laminates are cured on the curved jig plate, the curvatures of each stable state configuration are different from the curvature of the bi-stable structure from curing on the flat plate. Applying positive curvature jig plate curing induces a greater curvature of state 1 than the structure curvature of from the flat jig plate. (b) In the same manner, applying negative curvature jig plate curing induces less curvature of state 1 than that from the flat jig plate. However, curvature of state 2 is independent of the initial curvature curing effect. Applying either positive or negative curvature to the structure yields almost the same curvature shape as that from flat curing at state 2.

The reason for the initial curvature curing effect is not proven in detail here, yet it can be explained. Applying a curvature affects the total residual prestress in the CFRP bi-stable structure. In other words, a positive curvature produces a more curved shape and a negative curvature a more flat shape. From this result, we apply the $-8.33m^{-1}$ initial curvature curing process to the CFRP so that a leaf of the flytrap robot can have a small curvature in open state.

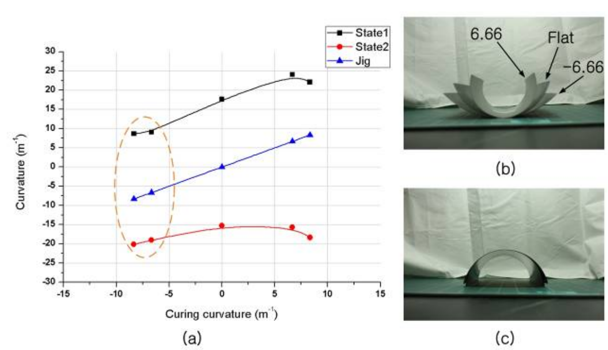

Fig. 4. (a) CFRP laminate curvature from various curvature jig plate curing process.(unclear: too long) orange dashed circle inside region shows that state one has small curvature and state two has large curvature.

B. Attachment of SMA Coil Spring Actuator

In the previous prototype of the flytrap robot, two bolt rods were mounted near the edge on the bi-stable structure and were connected with a SMA coil spring as described in Fig. 5 (a). This SMA spring shrunk to its original length by thermoelectric heating produced by the applied electric current and this shrinking force pulled the rods. Then the force generated a bending moment, using the rod as a moment arm, and made the bi-stable CFRP structure snap-through.

In this first prototype, the rods were so short that the SMA actuator induced a small bending moment. Also when the actuator activated to pull both end points, the middle of SMA spring touched the structure's surface. This led to an electric current leakage problem in which the current passed not through the SMA actuator but through a carbon fiber. Due to these issues, the SMA actuator in the previous flytrap robot generated limited power so that it cannot open the leaves of flytrap robot, and produced unstable activation.

To solve the problem, in the present prototype, we used three long bolt rods and drove the third bolt rod into the center of the bi-stable structure as in Fig. 5 (b). These long rods extended the moment arm length to increase the induced bending moment. Also, the additional center rod acted as a supporter to separate the SMA actuator from the surface of the CFRP. As a result, it prevented the actuator from contacting the carbon fiber.

Also, the arrangement of the actuator on the bi-stable CFRP structure was considered because deformation of the bi-stable structure by SMA actuators depends on the angle between the direction of the curvature axis of the structure and the direction of the activating force [9]-[10]. For this consideration, we attached the SMA spring along the circumferential line along the outside of the curved configuration. By attaching the spring this way, to the front and back side of the bi-stable CFRP structure, the flytrap robot was able to open and close.

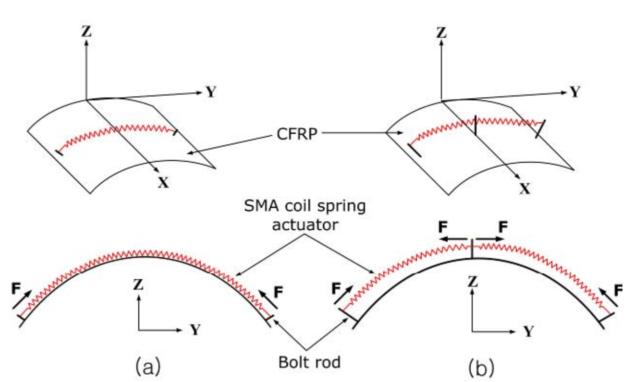

Fig. 5. Comparative scheme of attachment of SMA coil spring actuator on the bi-stable CFRP structure. (a) Small bolt rods induce small bending moment. Also the middle of spring contacts the CFRP surface. (b) The structure has three long rods which induces a large bending moment. The spring is now separated from the CFRP surface.

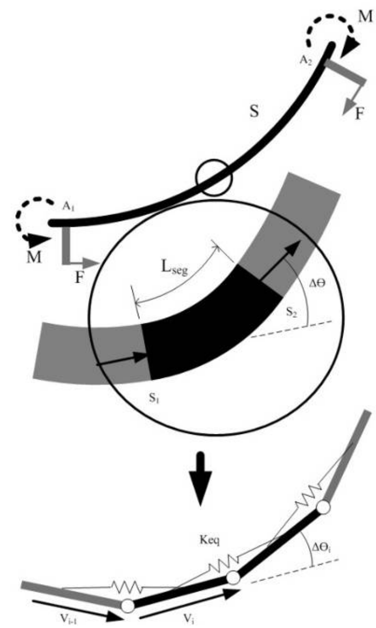

Fig. 6. Segmented linkage model for composite flexure.

III. MODELING

In this section, the segmented linear beam bending model is introduced to find the critical force that will induce the snap-through of the unsymmetric bi-stable composite structure. By this model, the deformation under a bending moment can be estimated. For the simple numerical approach, we assume that the bending moment at the edge of the structure is a pure bending moment that induces the snap-through of the structure, although the snap through is generated by the axial force of SMA spring actuator and the moment of bolt rods.

Deflection analysis of solid structures is carried out by equation (1). This equation is derived from the small deflection assumption for linearization [11]. Therefore, the application of this model in a composite flexure analysis is limited to small deflection angles. However, the bi-stable composite plate, which is the main structure of the robot, has large deflection angle of greater than 80 degrees, and the linear model is unsuitable for the bi-stable structure analysis. Thus, we propose a segmented linkage model based on a sufficiently short beam segment, as shown in Fig. 6. The model represents the bi-stable structure as several segmented linkages with springs at each joint. The length of the segment is short enough so that the linear beam bending model can be applied.

$$\frac{d\theta}{ds} \approx \frac{d^2 v}{dx^2} = \frac{M}{EI} \tag{1}$$

$$\Delta\theta = \int_{S_1}^{S_2} \frac{M}{EI} = \frac{M}{EI}(S_2 - S_1) \tag{2}$$

$$= \frac{M}{EI} L_{seg} \tag{3}$$

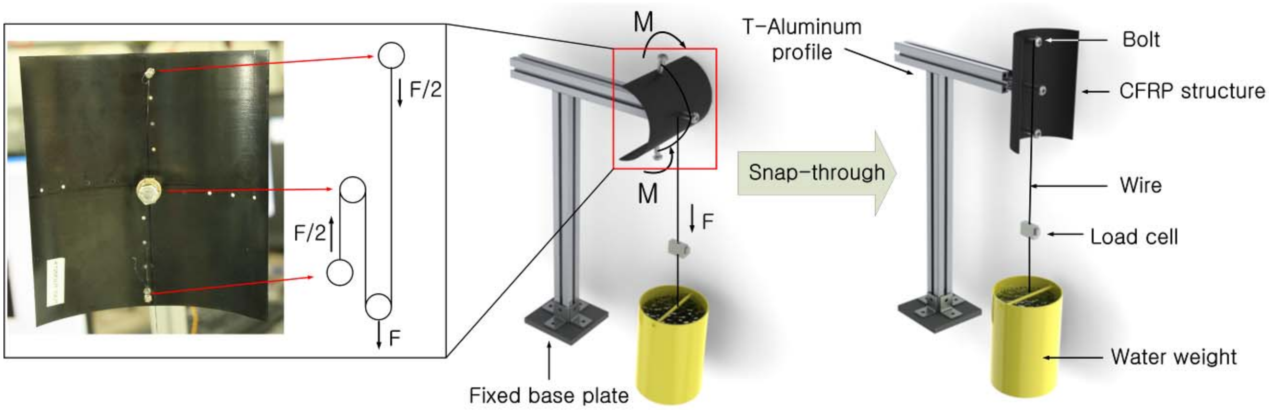

Fig. 7. Description of snap-through force measurement experimental setup. As the water weight increase, wire tension increases and bending moment at the bolt connected between wire and CFRP structure also increase. When the load reaches at critical point, CFRP structure changes its configuration from state 1 to state 2 via snap-through. M indicates bending moment and F indicates tensile force due to water weight.

$$M = k_{eq}\Delta\theta \quad (k_{eq} = \frac{EI}{L_{seg}}) \tag{4}$$

$$V_i = L_{seg}(\cos(\Delta\theta_i), \sin(\Delta\theta_i)) \tag{5}$$

$$S = \sum V_i \tag{6}$$

Basically, the deflection angle of a linear model is limited to about 4.7 degrees for linear approximation [11]. In this model, we determined that the limiting of the deflection angle of one segment is 1 degree, which is about 1 percent of the maximum bending angle of flexure at the end point. And L_{seg} can be obtained by equation (3) to be about 1mm. For obtaining the total deflection profile, the i-th segment of the model is represented by the position vector V_i, which is at an angle of $\Delta\theta$ from previous segment vector V_{i-1} (5). Finally, the flexure profile S is series connections of segment vectors (6). From the experimental result shown in the following section, the equivalent stiffness k_{eq} is determined by fitting the Young's moduli (E) of the fiber and matrix mixture. The value obtained from fitting was 130Gpa at state 1 and 100Gpa at state 2. The difference of the E value between the two states might be caused by the asymmetric layer lamination. Based on this result and model analysis, the critical condition and characteristics of composite snap-through phenomena can be explained.

IV. EXPERIMENT

In the previous investigation by Hyer, a simple loading experiment was conducted. In this experiment, the bending moment induced via water weight was applied to the two fixed points of the bi-stable structure to investigate the snap-through point [13]. We also tried this method because of its easy construction. The experiment was to determine the amount of force that had to be induced by the SMA spring actuator for snap-through of the bi-stable structure from one stable shape to the other stable shape.

To measure the force that induces the bi-stable structure to snap-through and to change its configuration, a force measurement system was set up, as described by the scheme of the system in Fig. 7. A T-shape aluminum profile structure was mounted on the ground base. The bi-stable CFRP structure was drilled at three points(:) one was at the center of the structure and the other two were near the edge along the curvature line of the structure passing through the center. Bolts were attached at that each of the three points. The center one held the CFRP structure to the T aluminum fixed end and also supported a pulling wire, and the other rods were the bending moment arms. The pulling wire is constructed by this way. A wire from the rod of the upper side came down straight and a wire from the rod of the lower side looped half way via the center support bolt. Both wires connected as one pulling wire. The pulling wire was attached in series to a load cell and the load cell was connected to a water container. Water as a load was added into the container through a small diameter straw tube, which was also used to control the flow rate slowly. When the load was increased, the pulling tension was monitored in LABVIEW through NI 9263 of C-series module.

Increasing the pulling load induced a bending moment at the upper and lower edges of the CFRP bi-stable structure. This bending moment stretched the structure until it became flat. To prevent friction between the half loop wire and the center

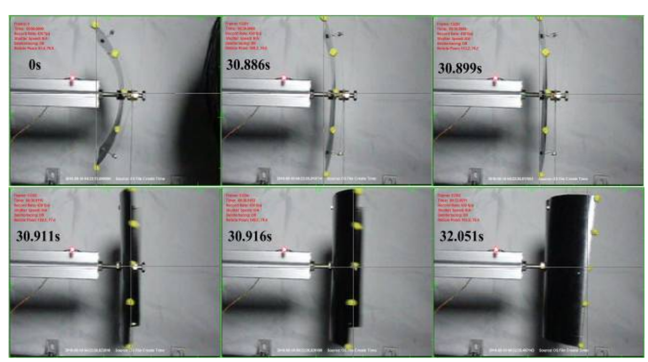

Fig. 8. Snap-through sequences of the bi-stable CFRP structure. Attached bold rod distance was 130mm and the moment arm was 15mm. The snap-through time was about 17ms.

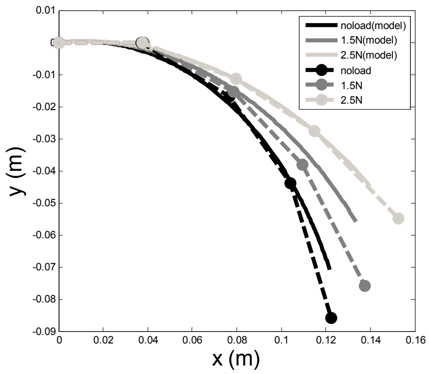

Fig. 9. Numerical result (solid line) and experimental result (dashed line) plot at state 1 of the bi-stable structure.

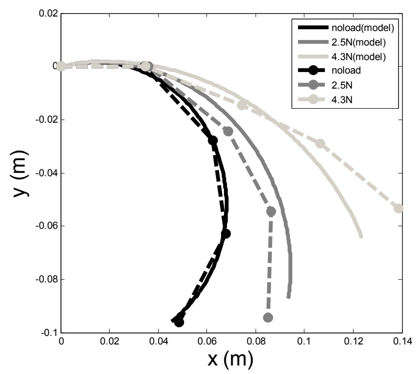

Fig. 10. Plot of numerical result (solid line) and experimental result (dashed line) at state 2 of the bi-stable structure.

bolt at this time, WD-40 was used as an antifriction.

When the load reached at critical point of snap-through, the CFRP structure changed its configuration rapidly.

The snap-through sequences in this experiment are shown in Fig. 8. High speed photographing was recorded by CASIO EX-FH 100 of 420 fps and the photographing data was analyzed using ProAnalyst.

The numerical result from the segmented linear beam bending model and the tracking position data of the bi-stable structure are plotted in Fig. 9 and Fig. 10, respectively. Though the numerical result and the force-displacement experimental result were quite different, the trend of deformation of the bi-stable structure under load could be identified. Based on the results, one SMA actuator should generate up to 2.5N to deform the bi-stable structure from its initial curved position to the position before snap-through. This result was reflected in the design of the SMA actuator.

V. Manufacturing

Each part of the flytrap robot was manufactured considering the design constraints. The unsymmetric bi-stable structure was made with two different curvature sizes for two states: curvature of about 10m^{-1} for one state and curvature of about 20m^{-1} for the other state corresponding to the open and closure state configurations. A SMA coil spring actuator which could generate the required force obtained

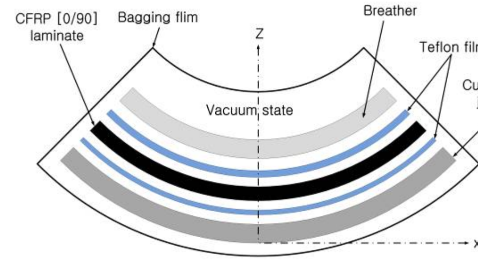

Fig. 11. The scheme of curing materials layup. In the notation [0/90], 0 layer means that the angle between the CFRP fiber direction and the jig plate curvature axis is zero.

from previous section was manufactured. With these components, a flytrap robot was built.

A. Bi-stable Leaf of Flytrap Robot

To make the bi-stable leaf have different curvatures at each state, the curve curing process is suggested and the curing layup of the materials arrangement in this process is shown in Fig. 11. The CFRP laminate of HANKUK CARBON CO. LTD. was used, the type was CU 0503. The properties of that model are listed in Table I. The two CFRP layers were trimmed to a square of 150mm in length. They were laid [0/90] on the jig plate with a curvature 8.33m^{-1}.

TABLE I
Carbon Fiber Prepreg Material Properties

Quantity	Unit	
Axial Tensile Modulus, E_1	GPa	230
Transversal Tensile Modulus, E_2	GPa	15
Shear Modulus, G_{12}	GPa	4.47
Poisson's Ratio, ν_{12}		0.3
CTE, α_1	°C^{-1}	0.19x10^{-6}
CTE, α_2	°C^{-1}	42.3x10^{-6}
Temperature change, ΔT	°C	-145

Mechanical properties are referenced on Hankuk Carbon Co. datasheet. The CFRP model type is CU0503. CTE is coefficient of thermal expansion.

The materials in the laminate curing layup were the Teflon film WL 5200B used to release from CFRP laminate layer, the bagging film WL 7400, and the breather ECONOWEAVE 1010 from AIRTECH CO. To establish a smooth upper surface of the CFRP laminate, the thick PTFE skived sheet film from KYUNG SHIN CHENPLA CO. was used before covering the breather. The curing process maintained the state at 170°C for 2 hour in the forced convection oven with vacuum bagging at 1atm.

B. SMA Spring Actuator

The required force of the SMA spring actuator was determined by analysis and experiment. In case of the bi-stable structure having 15mm moment arms and 130mm rod mounted distance, two actuators capable of producing a maximum force of 2.5N were needed to generate the snap-through action. Also to satisfy this constraint, the stretched length of the SMA actuator should be 130mm so the initial spring length was set to 25mm. To manufacture the SMA spring actuator which could generate 2.5N tensile force, the materials, an SMA wire, core rod, and a drill to wind the wire around the core rod, were prepared. SMA wire from DYNALLOY, INC. was used. Its diameter was 0.254mm and austenite temperature was 70°C.

Based on the manufacturing method of the SMA coil spring actuator presented in several investigations, the SMA wire was wound on a 1mm core-rod, which was vised on the drill [12]-[15]. From these parameters, a coil spring with a helical spring index of about 3.9 was used. After winding the SMA wire on the core-rod, both end-points of the spring were clamped and the spring was put into a stove for annealing treatment at 300°C for an hour. From this process, the SMA wire remembered the coil spring shape and produced a larger displacement than the general SMA wire. Therefore, a large curvature bi-stable composite structure can be stretched.

C. Prototype of Flytrap Robot

The flytrap robot prototype consists of three components. The leaves are made from two bi-stable unsymmetrically laminated CFRP composites. Two SMA coil spring actuators, which generate 2.5N force, are attached on each leaf. The leaves are mounted on the green base structure, which is made by the rapid-prototype (RP) machine of 0.254mm resolution. This base structure maintains the proper angle between the two leaves so that they close perfectly. The electrical wiring, which is constructed using an enamel coated wire, is built in series to synchronize the actuator on-off timing in each same-function (open or close) group.

VI. Result

The operation of the flytrap robot sequences are shown in Fig. 12. After a proper electric current is applied to the SMA actuator, the flytrap activates the snap-through motion and the robot opens the leaves and traps rapidly like the real Venus flytrap. The closure part of the snap-through takes almost 100ms.

The characteristic of the SMA spring actuator affects the performance of the robot. The SMA actuator needs relaxation time to cool down. If the SMA actuator activates on the front surface when the actuator, which is on the back surface, has not cooled down sufficiently, the actuator on the front surface interferes with the activation of the other one on the back surface. Therefore, the frequency of robot operation is limited.

Fig. 12. Flytrap robot performance sequences. Upper part shows the closing motion and lower part shows the opening motion.

VII. Conclusion

In this paper, we presented a flytrap robot which can open and close repeatedly with rapid snap-through motion. The robot was fitted with an appropriate curved bi-stable CFRP leaf and proper SMA coil spring actuators, which generate 5N force to induce snap-through the bi-stable structure. The performance of the flytrap robot is more powerful that from considering scale sides. The real Venus flytrap takes about 100ms to close the leaf of about 20mm in leaf size whereas this flytrap robot can close its leaf of 150mm in leaf size in the same amount of time. This result shows the potential of a morphing structure with large deformation and rapid motion, such as morphing wings, a rapid catcher, or a gripper. Future work will investigate several issues regarding the gripping force, SMA actuator control etc.

References

[1] Y. Forterre, J. M. Skotheim, J. Dumais, and L. Mahadevan, "How the Venus flytrap snaps," *Nature*, vol. 433, no. 7024 pp. 421-425, Jan 2005.

[2] S. Kim, J. Koh, M. Cho, and K. Cho, "Towards a bio-mimetic flytrap robot based on a snap-through mechanism," in *IEEE Int. Conf. Biomedical Robotics and Biomechatronics*, no. 5627994, pp. 534-539, Sept. 2010.

[3] M. W. Hyer, "Some Observations on the cured shape of thin unsymmetric laminates," *Journal of Composite Materials*, vol. 15, no. 2, pp. 175-194, March 1981.

[4] M. W. Hyer, "The room-temperature shapes of four-layer unsymmetric cross-ply laminates," *Journal of Composite Materials*, vol. 16, no. 318, pp. 175-194, July 1982.

[5] M. Schlecht, K. Schulte, and M. W. Hyer, "Advanced calculation of the room-temperature shapes of thin unsymmetric composite laminates," *Composite Structures*, vol. 32, no. 1-4, pp. 627-633, 1995.

[6] M. Cho, M. Kim, H. Choi, C. Chung, K. Ahn, and Y. Eom, "A study on the room-temperature curvature shapes of unsymmetric laminates including slippage effects," *Journal of Composite Materials*, vol. 32, no. 5, pp. 460-482, Mar. 1998.

[7] W. Hufenbach, M. Gude, and A. Czulak, "Actor-initiated snap-through of unsymmetric composites with multiple deformation states," *Journal of Materials Processing Technology*, vol. 175, no. 1-3, pp. 225-230, 2006.

[8] M. R. Schultz, M. J. Hulse, P. N. Keller, and D. Turse, "Neutrally stable behavior in fiber-reinforced composite tape springs," *Composites: Part A*, vol. 39, no. 6, pp. 1012-1017, 2008

[9] M. L. Dano and M. W. Hyer," Snap-through of unsymmetric fiber-reinforced composite laminates," *International Journal of Solids and Structures*, vol.39, no. 1, pp. 175-198, Jan 2002.

[10] M. L. Dano and M. W. Hyer, "SMA-induced snap-through of unsymmetric fiber-reinforced composite laminates," *International Journal of Solids and Structures*, vol. 40, no. 22, pp. 5949-5972, Nov 2003.

[11] S. H. Crandall, N. C. Dahl, and T. J. Lardner, "An introduction to the mechanics of solids", 2nd ed. Singapore: McGraw-Hill, 1978, pp. 512–514.

[12] S. Kim, E. Hawkes, K. Cho, M. Jolda, J. Foley, and R. Wood, "Micro artificial muscle fiber using NiTi spring for soft robotics," in *Proc. Int. Conf. Intelligent Robots and Systems*, pp. 2228-2234, 2009.

[13] K. Otsuka and C. M. Wayman, *Shape Memory Materials*. Cambridge University press, ch. 7, 1998.

[14] J. Koh and K. Cho, "Omegabot: Biomimetic inchworm robot using SMA coil actuator and Smart Composite Microstructures (SCM)," in *Proc. 2009 IEEE Int. Conf. Robotics and Biomimetics*, pp. 1154-1159, 2009.

[15] J. Koh and K. Cho, "Omegabot: Crawling robot inspired by *ascotis selenaria*," in *Proc. 2010 IEEE Int. Conf. Robotics and Automation*, no. 5509425, pp. 109-114, 2010.