Shape Memory Alloy Wire Actuated Hinge Mechanism for Deploying Segmented Plates

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Shape Memory Alloy Wire Actuated Hinge Mechanism for Deploying Segmented Plates

Tadakazu KATAYAMA*, Yoshihiko SUGIYAMA*, Satoshi KAWASHIMA**, Kohji NISHINO***

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The paper describes laboratory demonstrations of hinge mechanism actuated by a shape memory alloy (SMA) wire for deploying segmented plates. Nitinol wires are installed in two-plate model and three-plate model to deploy model plates. Radiant heating is used to heat and activate the actuator wires. Some considerations are given to arrangement and fixture of the actuator wires. The feasibility of the SMA wire actuated hinge mechanism is experimentally demonstrated for deploying the solar paddle in space. Numerical simulation is also conducted to find out the deploying behavior of the model plates.

1. Introduction

Performance requirements of advanced structural systems in the future, e. g., space structures, have motivated new concepts to structural and materials design. Wada, Fanson and Crawley[1] have proposed an idea to add intelligence to structural systems. Structures which incorporate environmental sensors, mechanical actuators and processing controllers have been termed "intelligent" or "smart" structures. Rogers[2] has given a general review on the intelligent structures.

As for actuators for intelligent structures, piezoelectric ceramics, shape memory alloys and electrorheological fluids have been installed in structures to control vibration and deformation of the structures[2]. Amongst the actuators, the shape memory alloys has a big advantage as an actuator, since it can act as a sensor and an actuator in its single existence and therefore provides a compact actuator with light-weightedness.

The shape-memory effect can be described basically as follows; an alloy in the low-temperature martensitic state, which is plastically deformed and whose external stress is removed afterward, will regain its original (i. e. memory) shape when heated. The phenomenological process is the result of a martensitic transformation taking place during heating. In order to be installed in a structure as an actuator, the shape memory alloy (SMA) must have a proper mechanical properties as an actuator. It has been known that Nickel-Titanium alloy called Nitinol has a good mechanical memory with excellent restoring force and considerable displacement capability. SMA actuators have been proposed for numerous applications, utilizing the strain recovery capabilities of Nitinol in torsion, bending and tensile elongation[2]. The application of SMA for pure tensile actuation was demonstrated by Hodgson[3] in 1988. Most remarkable application of SMA was demonstrated by Toki DH-101 Robot Arm[4]. The concept of the SMA actuated hinge was proposed and demonstrated by Anders and Rogers[5] in 1991. Under these circumstances of the applications of SMA as an actuator, the present paper deals with the experimental demonstration of a SMA wire actuated hinge mechanism for deploying segmented plates, the image of which comes from a solar paddle mounted on satellites. The original concept of SMA wire actuated hinge was demonstrated by Anders and Rogers[5]. It is noted however that they used an electrical current to heat up the actuator wires.

The intended aim of this paper is to demonstrate the reality of the hinge by using radiant heating to activate the SMA actuator wires, thus to show the feasibility of the hinge in use in space.

*Department of Aerospace Engineering, College of Engineering
**Graduate Student, Department of Aerospace Engineering, College of Engineering
***Fujikin Soft Corporation Ltd., Suminoe-ku, Osaka-fu, 559 Japan

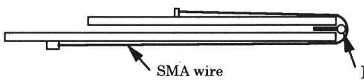
2. Concepts of SMA Wire Actuated Hinge Mechanism

A concept of the SMA wire actuated hinge mechanism is illustrated in Fig. 1 in case of the two plates connected by a hinge. Figure 1-(a) shows the folded configuration of the plates. A plastically elongated SMA wire is installed in the plates. Elongation of the wire is taken to be equal to the thickness of the folded plates. When radiant heating is applied to the SMA wire as shown in Fig. 1-(b) and the wire temperature exceeds the recovery temperature, the phase transformation of the SMA wire takes place. Then phase transformation from martensite to austenite gives rise to strain recovery. Thus the wire tension induced by the strain recovery yields a moment about the hinge, causing the moving plate to deploy as illustrated in Fig. 1-(c). As the strain is recovered in full, the moving plate is deployed fully as shown in Fig. 1-(d).

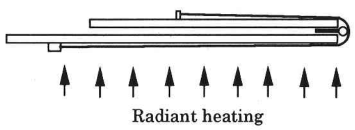
3. Experimental Demonstration

3.1 Experimental setup

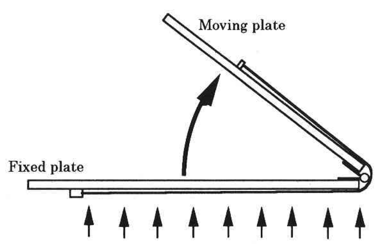
Overall view of the experimental setup is shown in



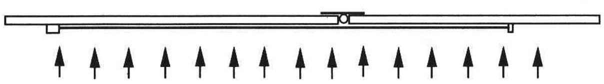
(a) Stage I: Plastically elongated SMA wire at room temperature



(b) Stage I' : Radiant heating is applied to activate the wire



(c) Stage II: Thermally induced phase transformation causes the wire to contract and thus to create the moment around the hinge to deploy the model plates



(d) Stage III: The moving plate fully deployed

Fig. 1 Concept of SMA wire actuated hinge mechanism

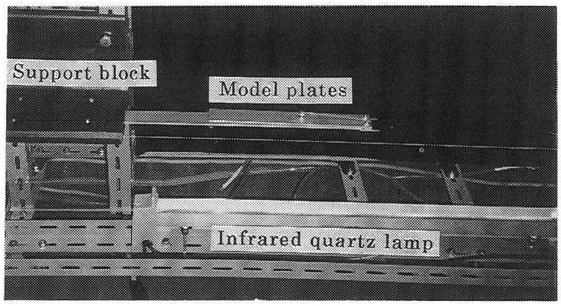
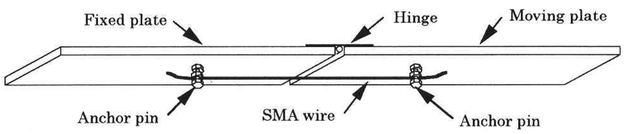
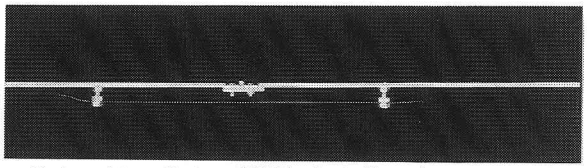


Fig. 2 Overall view of the experimental setup

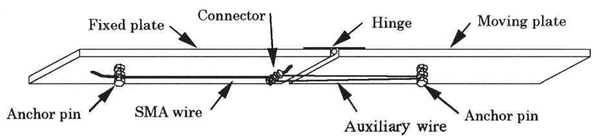


(a) SMA wire in Type A arrangement

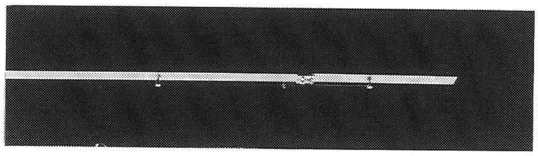


(b) Actual installation of SMA wire in Type A arrangement for the two-plate model

Fig. 3 Two-plate model with type A wire arrangement

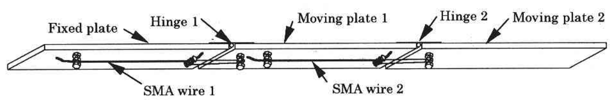


(a) SMA wire in Type B arrangement

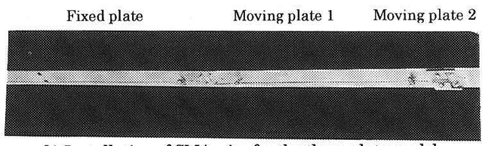


(b) Actual installation of SMA wire in Type B arrangement for the two-plate model

Fig. 4 Two-plate model with type B wire arrangement



(a) Wire arrangement in three-plate model



(b) Installation of SMA wire for the three-plate model

Fig. 5 Three-plate model

Fig. 2. The new idea in the present demonstration is to use a infrared quartz lamp to heat the SMA wire. The infrared lamp of heated strip of dimensions 28×500mm has the maximum power of 4kw. Model plates are arranged in parallel with the infrared heat lamp and held horizontally by the support block to minimize the effect of gravitational forces on the plate movement.

3.2 SMA wire

The shape memory alloy wires used in the present experiment were Nitinol (50.6at%Ni) with the recovery temperature of 60°C. The diameters of the SMA wires were 0.6 and 0.7mm. The SMA wires were plastically and uniformly strained by an Instron-type tensile testing machine up to 5% at room temperature before they were installed. In practice, the SMA wire of length of 200mm was made to have the plastic elongation of 10mm. The maximum tensile stress applied to the wire with the diameter of 0.6mm was 30 kgf/mm^2 (294 MPa). It is noted that an important issue to have in mind in using Nitinol wire is that brazed or soldered connections are structurally unacceptable.

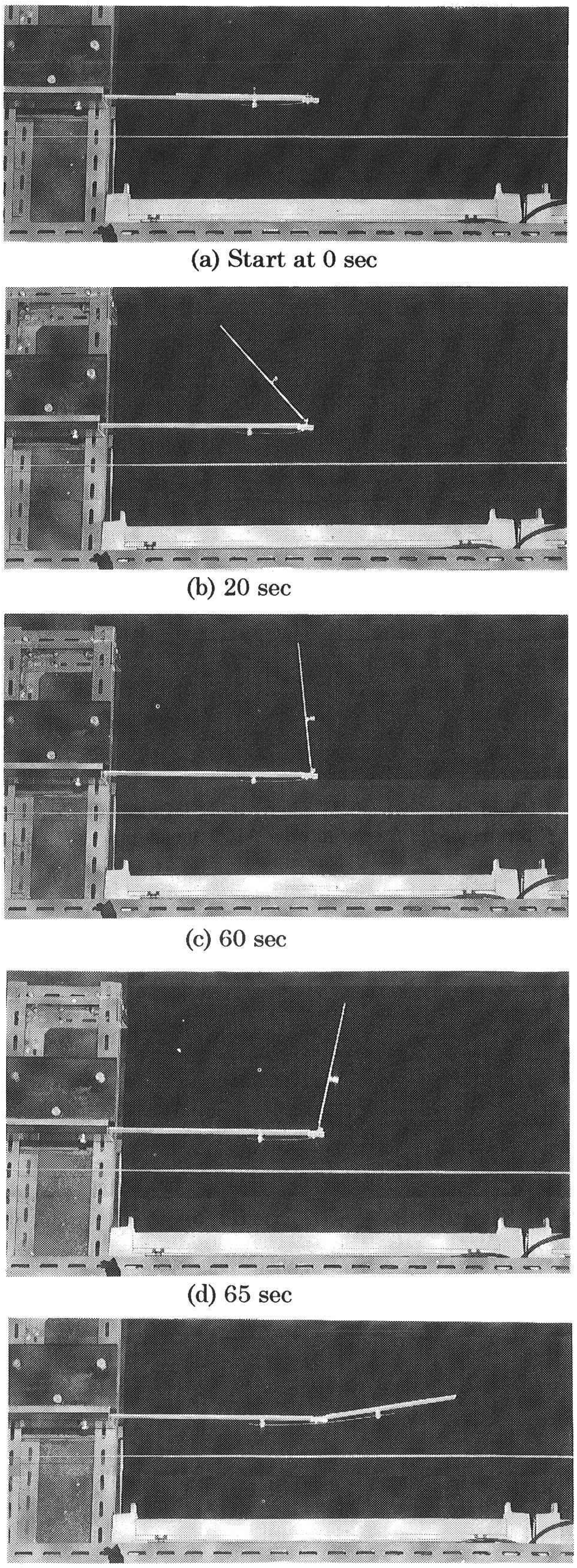
3.3 Model plates

The model plates consist of two or three plates connected by hinges. The left plate is fixed, while the right one is movable. Model plates which consist of two rigid plates connected by a hinge is here referred to as two-plate model as shown in Figs. 3 and 4, while the model of three rigid plates is referred to as three-plate model as shown in Fig. 5. The anchor pins were fixed to the plates to clamp the wire. Equally to the wire elongation required to fold the plates, the amount of elongation of the wire is trimmed by changing the anchor pin position.

Two types of wire arrangement were devised for the two-plate model. In Type A arrangement as shown in Fig. 3-(a), the SMA wire was installed over the two plates. In Type B arrangement as shown in Fig. 4-(a), the SMA wire was installed only on the fixed plate and the auxiliary wire connected the SMA wire and the anchor pin on the moving plate. Figures 3-(b) and 4-(b) show the actual installation of the SMA wire on the experimental model. Type B wire arrangement is applied to the three-plate model as shown in Fig. 5.

3.4 Demonstrations

Figure 6 shows the observed motion of the two-plate model during deploying operation. Figure 7 shows the measured deployment angle in time for the case of the



(a) Start at 0 sec

(b) 20 sec

(c) 60 sec

(d) 65 sec

(e) 90 sec

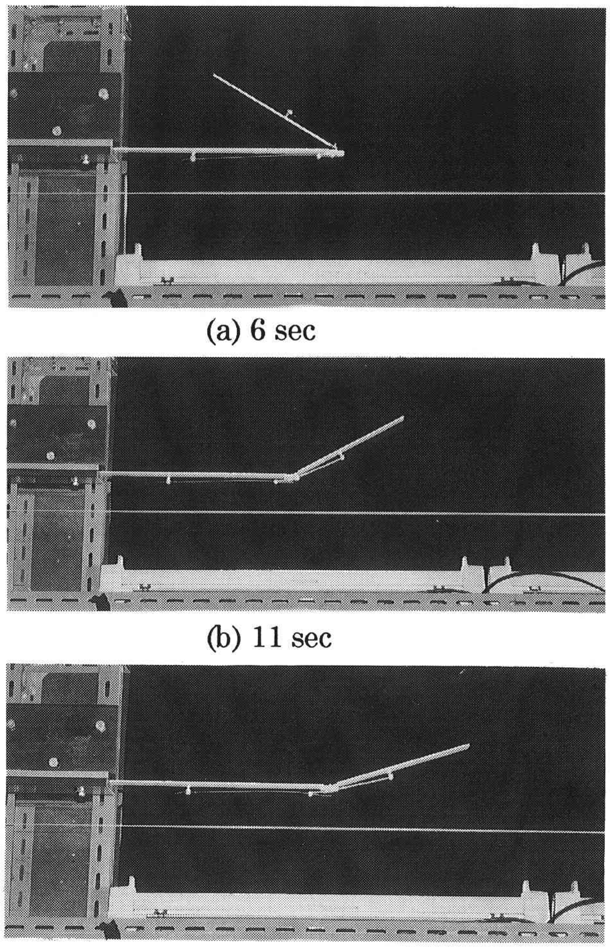
Fig. 6 Sequential photographs of the two-plate model in deployment: SMA wire in type A arrangement type A wire arrangement. Five test runs were conducted. As soon as the start of heating, the plate begins to move very slowly. Then SMA wire is activated within a few minutes to cause phase transformation. At the deployment angle of 60° to 90°, deployment speed becomes extremely low. Because of the geometrical relation between the heating lamp and the SMA wire, only a small temperature rise can take place in the wire on the moving plate. After the moving plate was deployed more than 90°, the SMA wire on the moving plate began to be heated. Then the rapid strain recovery of the wire on the moving plate took place and the moving plate was deployed quickly. It is interesting to note that in case of the test run Nos. 1 and 5 the friction at the hinge disturbed the deploying motion of the moving plate.

Figure 8 shows the deploying motion procedure of the two-plate model with the wire in type B arrangement. Three test runs were made. The measured deployment angle in time is shown in Fig. 9. It is noticed that the test run No. 2 had a friction trouble at the hinge. This type of wire arrangement makes the whole SMA wire heated concurrently. The moving plate was opened to at 20° within 3 seconds after heating. The moving plate was opened in a line with the fixed plate by 13～20 seconds.

Figure 10 shows the deploying motion of the three-plate model. In about 5 seconds after heating, the moving plate 1 began to deploy. In about 17 seconds the deployment angle of the moving plate 1 was above 90°. Then the SMA wire installed on the moving plate 2 was exposed to the radiant heating. In about 26 seconds the moving plate 1 deployed in full and the moving plate 2 began to deploy since the SMA wire on the moving plate 1 was exposed to the radiant heating over all.

4. Numerical Simulation

To evaluate the effect of design parameters on the hinge mechanism, a numerical simulation was conducted to predict the deployment angle θ of the moving



(a) 6 sec

(b) 11 sec

(c) 14 sec

Fig. 8 Sequential photographs of the two-plate model in deployment: SMA wire in type B arrangement

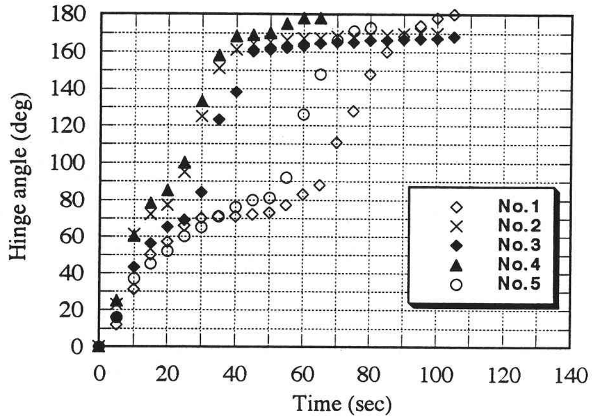


Fig. 7 Hinge angle in time (Two-plate model; type A)

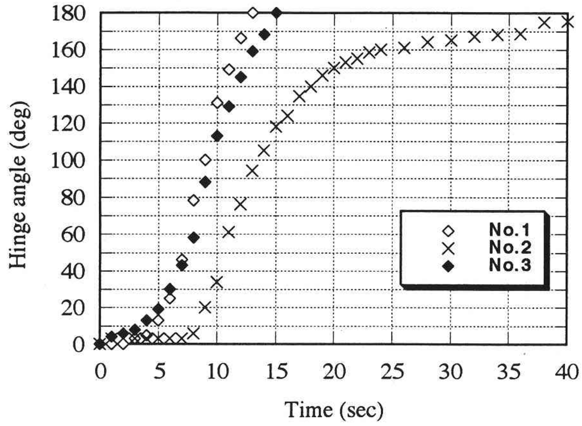
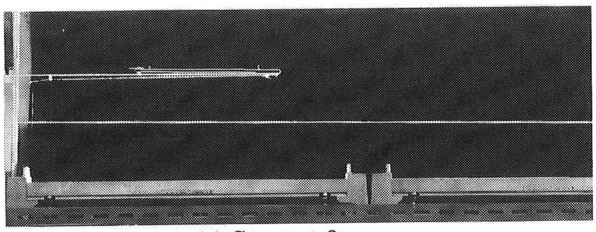
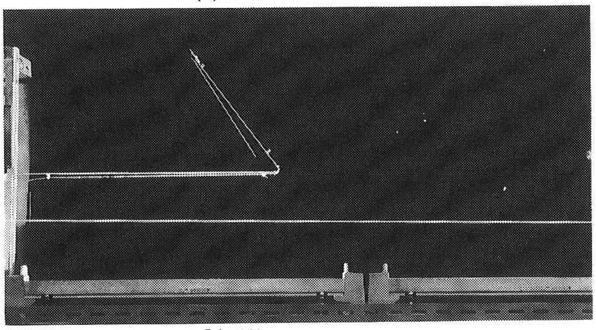


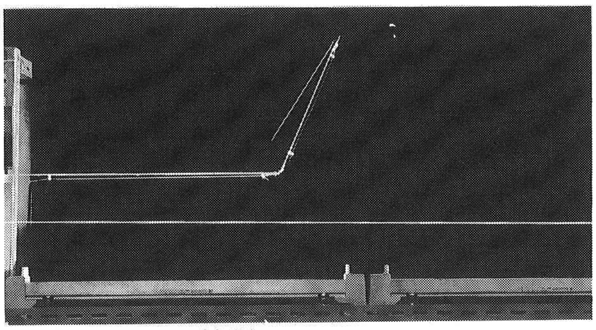
Fig. 9 Hinge angle in time (Two-plate model; type B)



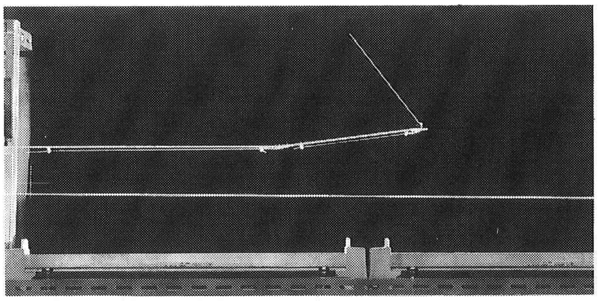
(a) Start at 0 sec



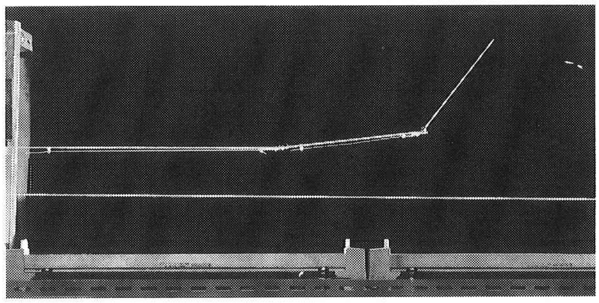
(b) 15 sec



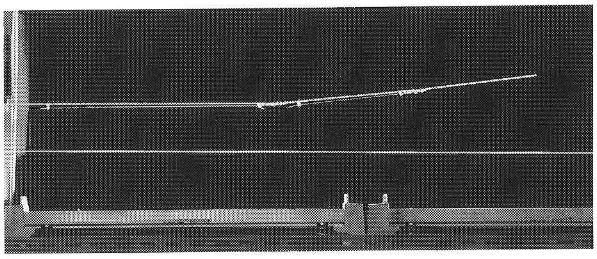
(c) 21 sec



(d) 27 sec



(e) 32 sec



(f) 37 sec

Fig. 10 Sequential photographs of the three-plate model in deployment

plate for the two-plate model with the SMA wire in type B arrangement. The mathematical model is shown in Fig. 11. The forces applied to the moving plate are a wire tension, an air resistance and a friction at the hinge. Equation of motion of the moving plate is obtained by considering the equilibrium of moment about the hinge. The equation is written in the form

$$I\ddot{\theta}+\frac{1}{3}Kl^3\dot{\theta}+2\mu_1 T(\theta)\left[1+\cos\frac{\theta}{2}\right]r-T(\theta)h=0, \quad (1)$$

where, I is the moment of inertia of the moving plate about the hinge axis, h is the thickness of the plate, l is the length of the moving plate, θ is the angle between the moving plate and the fixed plate, $T(\theta)$ is the recovery force of the SMA wire, K is the damping coefficient of air resistance, μ_1 is the friction coefficient of the hinge, and r is the radius of the hinge.

Equation (1) is discretised in time by applying the finite difference method. The deployment angle is obtained numerically step by step in time. A simulation result is depicted in Fig. 12. Comparing Fig. 12 with Fig. 9, it is seen that the deployment angle of the two-plate model is simulated qualitatively well.

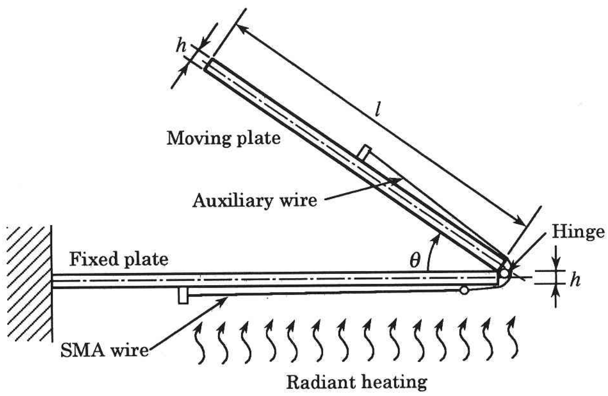


Fig. 11 Mathematical model of the two-plate model with type B wire arrangement

5. Concluding Remarks

The Nitinol wire actuated hinge mechanism was implemented in plate models in laboratory. Experimental demonstrations of the deployment of the plates

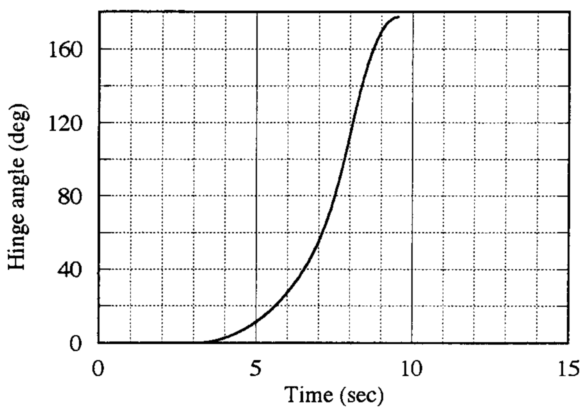


Fig. 12 Hinge angle by the numerical simulation for the two-plate model with type B wire arrangement

were conducted to confirm the feasibility of the hinge mechanism in use in space structure. Originalities of the present experimental demonstrations are as follows;

1) Radiant heating which simulates the solar heating was used to heat and activate the Nitinol wire.
2) A new type of wire arrangement was devised for smooth deployment of the plates.
3) Sequential deploying of the two plates was demonstrated in case of the three-plate model.

To give better understanding of the deploying behavior of the plates by means of the shape memory alloy wire actuated hinge mechanism, the dynamic model has been proposed and numerically studied. It has been found that the dynamic mathematical model can simulate the deployment angle of the moving plate qualitatively well.

Application of the shape memory alloy actuator to more complicated built-up structural systems are foreseen.

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