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Design of a Deployable Antenna Actuated by Shape Memory Alloy Hinge

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Abstract。 This paper is concerned about a design of a new deployable antenna actuated by 6 shape memory alloy (SMA) hinges. The antenna consists of 6 radial, tensioned, parabolic, deployable ribs connecting to a central hub. The hinge, located at each rib, is used of the Nitinol SMA material due to the ability to generate large strains and electrical resistive actuation. The elongated SMA wire is heated by an electrical current, caused to contract in response to a converse thermally-induced phase transformation. The resulting tension creates a moment, imparting rotary motion between two adjacent beams. The concept and operation of deployable antenna system are discussed in detail, and a dynamic simulation is presented. A series of experiments are performed on the SMA actuator to investigate the system behavior in the process of deployment. Results indicated that the hinge with low speed rotation and easy fabrication achieves reliable actuation for the deployment of the antenna, and the antenna demonstrates a high deployment-to-stowage volume ratio.

Introduction

New satellite communications and earth observation technologies have been emerging at a dramatic pace over the last decade. The advanced requirements related to antenna suggest some form of advanced beam steering and beam forming capability. While phased array systems allow shaping of the antenna far-field pattern, the use of phased array technology in space has been somewhat limited. The reasons are the high weight, complexity and cost of phase array systems[1]. The most common type of deployable antennas is the mesh antenna with a reflective surface composed of a knitted lightweight metallic mesh. Although the mesh is discontinuous, it can reflect radio frequency (RF) waves up to about 40 GHz [2]. Deployable mesh antennas are available in many configurations which differ in the way the mesh is supported [3, 4, 5].

SMAs have been used in a wide variety of applications because of their unique thermomechanical characteristics. The SMA elements have been made in the following shapes [6]: 1. Straight wires in tension, for small linear motion/high force; 2. Helical elements, for large linear motion/small force, or large rotation/small torque; 3. Torsion bar/tube, for large rotation/small torque[7]; 4. Cantilever strips, for large displacement/small force; 5. Belleville-type discs, for small linear motion/high force. Generally speaking, only large deformations or large forces can be obtained from SMA, but not both. The findings of this paper show a new and low-cost approach to a new antenna pattern actuated by SMA hinges(Fig.1).

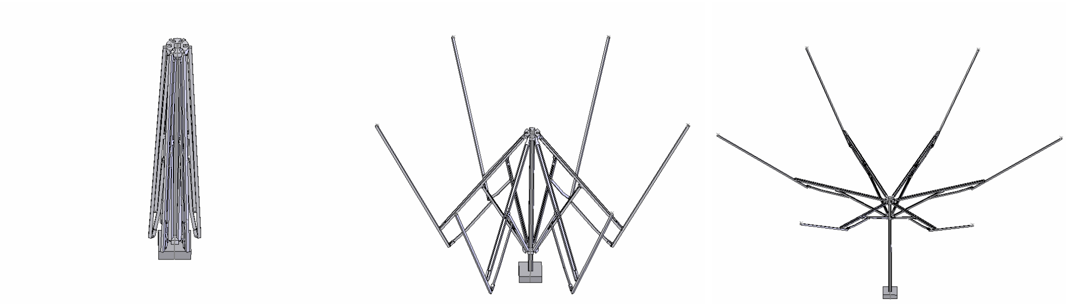
Design of the deployable antenna

The design of a 1.4 m diameter umbrella-type prototype is presented in this paper. The stowed diameter and height are 0.17m and 0.50m, respectively. The total weight is 2.53kg .The antenna is composed of a deployable truss structure(Fig.2) and a reflective membrane surface(Fig.1).

The deployable truss consists of six radial, tensioned, deployable ribs connecting to two central hubs on the center axis. Each rib(Fig.3)with the shape of triangle and parallelogram contains four beams. Beam 1 is connected to the upper hub, and beam 2 is connected to the lower hub. The upper hub is fixed on the center axis, and the lower hub can move along the center axis. When the lower hub moves towards the upper hub, one side of triangle contracts, the parallelogram deploys at the same time, and the truss structure deploys from stowage to deployment.

Fig.1 Deployable Antenna Actuated by Shape Memory Alloy Hinge

The reflective surface is composed of two layers, the reflective membrane and the glass-fiber mesh. The strength of the reflective membrane is weak, so the glass-fiber mesh with high strength is made for the reinforcement for the reflective membrane.



a. Stowage b. Intermediate deployment c. Final Deployment

Fig.2 Process of deployment for the deployment truss

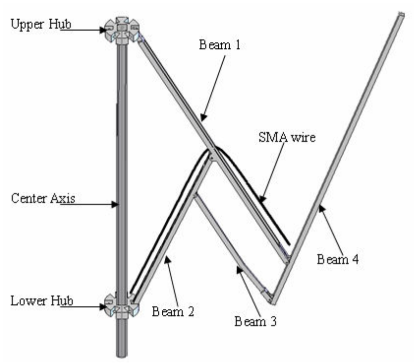


Fig.3 Deployable rib element for truss

Design of the SMA actuator

The SMA wire can provide the stress as strong as 700MPa with completely constraint, and can provide the 7% revertible strain without constraint, which is large due to normal materials but too small due to the demands of actuator. The SMA spring actuator with the character of large strain for small structures is reported frequently, but the stress is weak. Also, the SMA wire actuator with the character of strong stress is often reported, but the actuating displacement for the structure is small. The main character of the SMA actuator in this paper is that the large angle motion with the small strain of SMA wire can provide enough actuating force due to the large stress of SMA wire.

The SMA deployment hinge(Fig.4), located at each rib, is used of the Nitinol(NiTi) SMA material due to the ability to generate large strains and electrical resistive actuation. Six NiTi wires of length 0.42m each and diameter 0.8mm were fixed on the different beams for the actuation (Fig.3, Fig.4).The SMA is completely in martensite phase at room temperature(25°C) .The SMA wires are fixed between the two points due to beam 1 and beam 2. When heating the SMA wires of the actuator these wires contracted in response to a converse thermally-induced phase transformation. The resulting tension creates a moment, imbeaming rotary motion between two adjacent beams. And the motion follows the equation below:

$$\frac{(\theta_t-\theta_0)\pi R}{180(L_1+L_2)+(180-\theta_0)\pi R}=\varepsilon \quad (\theta_t>\theta_0, 0<\theta_0,\theta_t<180^\circ) \qquad (1)$$

Where θ_0, θ_t are the original angle and terminal angle between the adjacent beams respectively, ε is the strain for SMA wire. L_1, L_2 are the length of the beam 1 and beam 2 respectively, R is radium of the hinge.

Experiment and results

To measure the motion property of the deployment for the antenna, the displacement-time curve of the center hub was measured. First, the SMA wires in martensite phase were elongated by 4% at room temperature then fixed on the six ribs of the antenna. Second, the center axis of the antenna was positioned horizontally to ignore the influence of gravity, and the six series-wound SMA actuating wires of the antenna were heated with the current (2.5A). The result data points of displacement-time was measured by precision camera, and the displacement-time curve(Fig.5) was gained. The total deployment time was 46 seconds, and the displacement of hub was 0.3590m.The length between the two hubs in the deployment state was 0.8538m, and the angle between Beam 1 and Beam 2 was 164.65°.The displacement-time curve indicates that in the original and terminal phase the velocity of the hub is lower than the intermediate phase. It can be explained that the inertia of the antenna baffled the movement in the original phase, and the tension of the reflective surface decelerated and finally stopped the hub in the terminal phase.

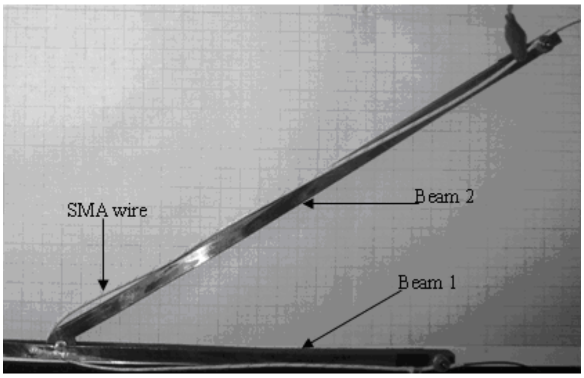


Fig.4 The SMA deployment hinge

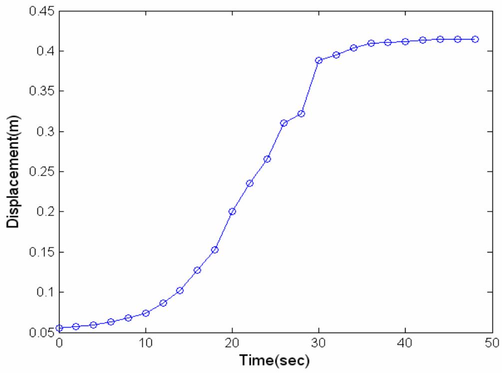


Fig.5 Displacement-time curve of hub

Dynamics simulation and results

To ensure the secure deployment and indirectly measure the motion property for the deployment, the dynamics simulation was done. Based on the experimental displacement-time curve(Fig.5), the angle-time and force-time curve of SMA actuator were measured using the dynamic simulation. First, a translational joint motion was applied to the simulative hub which moved along the experimental displacement-time curve, and the simulative angle-time curve(Fig.6) of the SMA actuating hinge was gained (Because the experimental angle -time curve of SMA hinge was difficult to measure, the curve of hub was measured instead). Second, a rotational joint motion was applied to the 6 SMA hinges which moved along the angle-time curve above. Finally, the simulative equivalent force-time(Fig.7) curve of the SMA actuating hinge was gained due to the motion of SMA hinge.

The comparison between Fig.5 and Fig.6 indicates that the motion of hub and SMA joint holds the linear relation. Because it is difficulty to simulate the friction of the joint, it should be noted that the force in the force-time curve(Fig.7) is just the equivalent force for the combinational effect of SMA actuating force and the friction of the joints. Fig.7 also shows that the process of the motion is not stable enough.

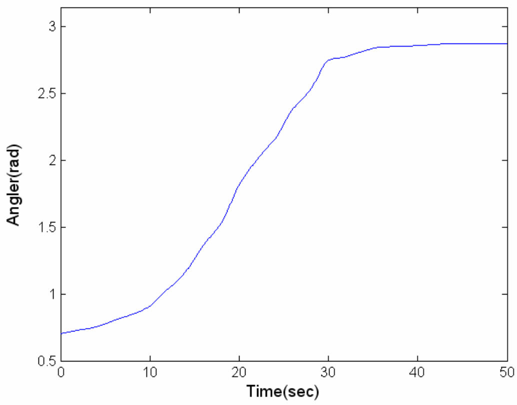


Fig.6 The angler-time curve of the SMA hinge

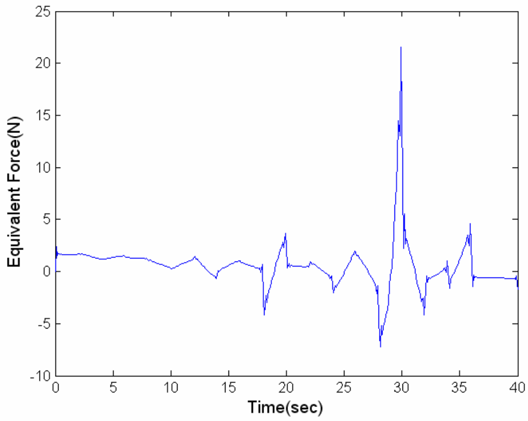


Fig.7 the equivalent force–time curve of the SMA hinge

Conclusions

The SMA actuator designed in this paper holds the main character that the large angle motion with the small strain of SMA wire can provide enough actuating force for the deployment of the antenna. The hinge with low speed rotation, and easy fabrication achieves reliable actuation for the deployment of the antenna, and the antenna demonstrates a high deployment-to-stowage volume ratio. The combination of structural system and simple SMA actuator reduce the mass of the deployable antenna.

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