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ACTUATION MECHANISM USING SHAPE MEMORY ALLOY WIRES IN SPIRAL ARRANGEMENT FOR MORPHING WINGS

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Abstract

Shape Memory Alloy (SMA) wires have received a lot of attention to be used in actuator for morphing wing. SMA exhibits a large recovery stress when the wires are heated over transformation temperature. Additionally, SMA actuator weight can be lighter compared to conventional hydraulic actuation system because the actuator does not need a complicated mechanism. This research presents a new actuation system for morphing wings by arranging SMA wires spirally. The spirally arranged SMA wires save the space for locating longer wires that is necessary for the large actuation stroke. However, the friction between the wires and spirally-arranged tube cannot be neglected and must be understood in detail to design the actuator. This paper experimentally evaluate the effectiveness and the limitation of the spiral arrangement of the SMA wires.

Keywords: Shape Memory Alloy, Actuator, Morphing, Friction

1. Introduction

Recently, much attention has been drawn to the reduction of fuel consumption in aircraft. Therefore, morphing wings have been developed as a key to the solution. This wing leads to the reduction of drag, improving the lift drag ratio by optimized deformation during flight situations. [1] Shape Memory Alloy (SMA) wires have received attention to be used in actuator. SMA has remarkable characteristics such as desirable recovery stress and deformation per unit mass when wires have been heated over transformation temperature. Additionally, actuator weight is lighter compared to conventional hydraulic actuation system because of lightweight material. [2]

Recent researches on morphing aircaft have attracted a lot of attention from aerospace structures community. The topics on recent morphing researches include flexble skins and SMA-based lightweight actuators [3] to allow larger deformation of the wing surfaces. In previous study on lgihtweight actuator for morphing wing, Ikeda et al. showed that actuation system using antagonistic SMA wires has a possibility to hold actuator position without external electirc power. [4] In this method, the hysteresis of the SMA wire is used to hold the actuator position although the impulsive electirc power is supplied to heat the one SMA wire in short period. After stopping the heating, the part of the displacement in the actuator remains without heating. Thus, not only lightweight but also low-energy acuator system for morphing wing can be realized. On the other hand, the authors have also designed and developed an actuation mechanism by which flexible flap was drived. [5] Wind tunnel test was also conducted and it was confirmed that it could be used to drive flap up and down.

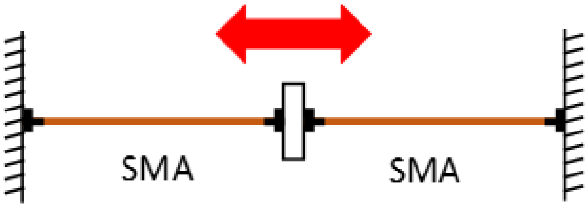
In our recent study, by extending the study by Kojima et al.[5], we apply the antagonictic SMA wires to drive the flexible flap. [6] This study further investigates to increase the flap angle of the morphing wing by properly designing the antagonistic SMA actuator in spiral arrangement.[6] Altough Helps et al showed that one loop of the spiral arrangement is the best condition due to the increase of the frictional force [7], few study clearly showed the what is suutable design parameters and the limitation of the spiral arrangement of the wire.

This research presents a new actuation system for morphing wings leading to improvement of displacement by arranging SMA wires spirally. Our previous study showed that ideal flap angle ±10 ° was not achieved due to insufficient force and displacement obtained from wire. The maximum strain is limited; hence increasing the length of wire is a significant perspective to deal with this issue.

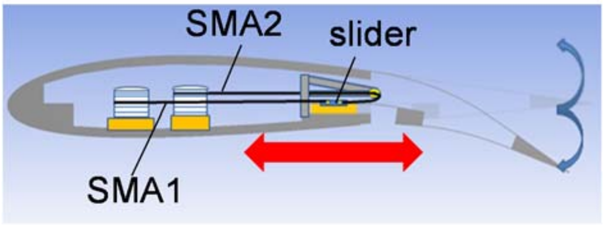
2. Actuator Using SMA Wires in Spiral Arrangement

2.1 Actuator with Antagonistic SMA Wires

The SMA wire used in this experiment was a TiNi SMA wire (YOSHIMI INC). The principle of driving the antagonistic SMA wires is shown in Fig. 1(a). In Fig. 1(a), pre-strained two SMA wires are connected on the slider in the center of the actuator. If one of the wire is heated, the slider moves according to the direction of heated wire. Figure 1(b) shows an image of the whole system to drive the morphing flap. In Fig. 1(b), if the SMA 1 is heated the flap deforms down whereas if the SMA 2 is heated, the flap deforms up. Note that the control force is given to the flap at only one point, which means the flap shape is changed by aerodynamic force even if the slider position is kept. Therefore, the stiffness of the flap is important to maintain the required flap shape.



(a) Antagonistic SMA wire actuator image



(b) Flap drive image by competitive SMA

Figure. 1. Actuator mechanism image: (a) Antagonistic SMA wire actuator image; (b) Flap drive image by antagonistic SMA

2.2 Basic experiment of spiral arrangement

This section explains the new type of the SMA wires arrangement: spirally guided SMA wires. Figure 2 shows the image of the spiral configuration of the SMA wires. To save the space for the longer SMA wires, we proposed to take SMA wires in spiral configuration as shown in Fig. 2.

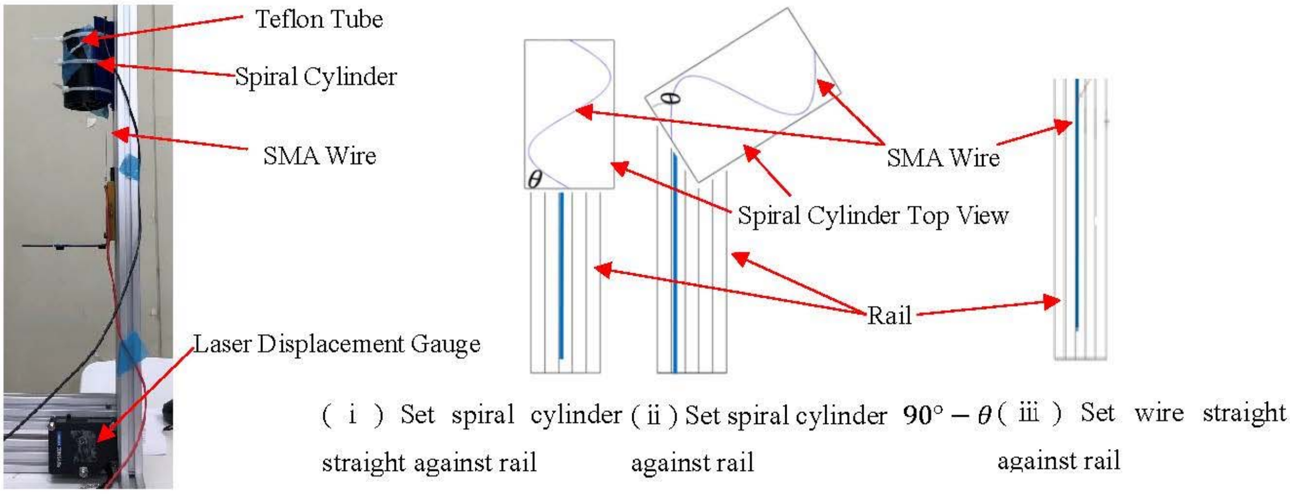
In order to arrange wire spirally, cylinders with a spiral path is used. When spiral angle θ is $\theta \leq 30°$, 2 times more length of wire can be stored compared to straight wire. Teflon tube is fixed to cylinder surface followed by spiral path. By putting wires through the tube, spiral arrangement is feasible. Experiment is performed to evaluate the results of displacement respectively to straight and spiral situation. Cylinder, linear slider is fixed to aluminum rail and displacement is measured by laser displacement gauge (Figure 3). Experimental equipment is set vertically so that constant force (5.88N) could be applied during measurement. The wire near the start and end of the Teflon tube cylinder is bent and not straight. Therefore friction is concerned so three kinds of experiments were carried out (Figure 3). In (i), (ii), linear and spiral segments of wire are included in each situation.

Figure 2: SMA Wires in spiral arrangement. SMA wires are guided in Teflon tube in spiral configuration.

The assumption has been made that the strain of wire inside and outside the cylinder differed significantly. According to the results of linearly arranged wire (iii), the strain is 4.9%. Thus, the strain in linear segment (i), (ii) is predicted to be 4.9%. Define, maximum displacement (outside spiral) ∆x_o, length of wire l_total=300mm, spiral lengthl_s=200mm, maximum displacement (inside spiral) ∆x_i, maximum displacement (Total) ∆x_total, strain (inside spiral) ∆ε_i, length of cylinderl_c=100mm, linear wire displacement (length of cylinder) ∆x_c.The calculation has been done from the following steps written below.

① $\Delta x_o = (l_{total} - l_s) \times 0.049$
② $\Delta x_i = \Delta x_{total} - \Delta x_o$
③ $\Delta \varepsilon_i = 100 \times \Delta x_i / l_s,$
④ $\Delta x_c = l_c \times 0.049$

2.3 Experimental setup for basic experiments



(i) Set spiral cylinder straight against rail

(ii) Set spiral cylinder $90° - \theta$ against rail

(iii) Set wire straight against rail

Figure 3: Experimental setup for basic verification of the spiral SMA wires.

Table1. Experiment Results for the basic experiments.

Experiment Type	(i) Straight	(ii) 90° − θ	(iii) Straight
Spiral Angle θ(degree)	30	30	
Strain (outside spiral) $\Delta\varepsilon_o$ %	4.9	4.9	4.9
Strain (inside spiral) $\Delta\varepsilon_i$ %	3.6	3.9	
Improvement of displacement ratio $\Delta x_i/\Delta x_c$	1.5	1.7	

2.4 Results for the basic experiments

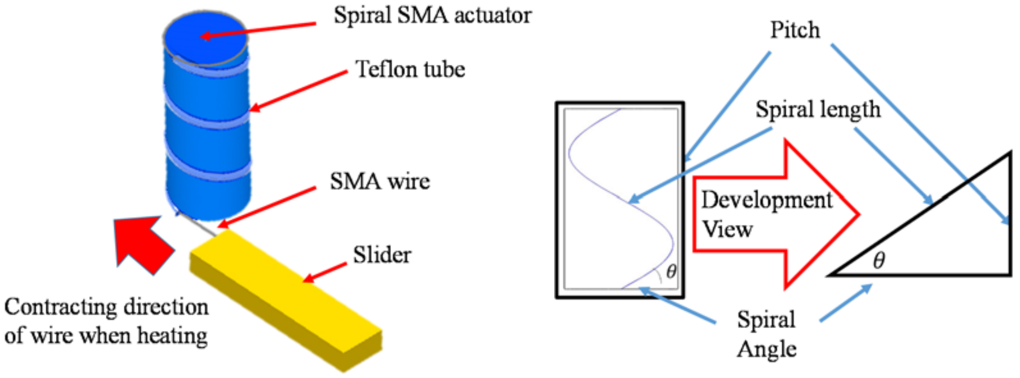
The results shown in Table 1 are an average of 5 times. The table 1 shows the strain decreased 1.3% in (i), 1.0% in (ii) compared to (iii), respectively. Arranging wire spirally in spiral angle θ=30° makes it possible to place 2.0 times longer length of wire in contrast to straight wire. On the other hand, the strain has fallen to 3.6% in (i), 3.9% in (ii), respectively. However, assuming that straight wires are placed straight equal to the length of cylinder, the improvement displacement ratio compared in length of cylinder between (i) and (iii) would be 1.5, (ii) and (iii) would be 1.7. As a result, the spiral arrangement has positive effect in terms of increasing the displacement of SMA wire.

2.5 Discussion on the limitation of the spiral SMA wires

Due to the friction between the SMA wires and the inner surface of the Teflon tube, the actuation of the SMA wires cannot work when the friction force is too great to move the SMA wires relatively to the surface of the tube. Theoretically, it is shown that the frictional force between the wires and inner surface of the tube increases exponentially if the contact of the wire is perfect [8]. However, no experimental data has been reported. Therefore, we investigate the relationship between the wrapping angle and the available recovery strain that is also equivalent to the actuation performance.

2.6 Experiments on the limitation of the spiral arrangement

Table 2 shows the spiral settings for the experiments. The spiral angle is a constant value but the wrapping angles varies so that the spiral length varies too. The storage ratio is always four because the ratio is changed only when the spiral angle varies. Figures 4-6 show the experimental setup. As shown in Fig. 5, the wire has spiral and straight parts where the friction force can be applied only for the spiral parts. Therefore we evaluate the recovery strain for the wire in spiral parts.



(a) Setup of the SMA actuator (b) definition of the spiral angle and pitch

Figure 4: Configuration of the spiral SMA actuator and the linear slider to evaluate the available actuation stroke (i.e., recovery strain of the SMA wire).

2.7 Results and discussion

Table 3 shows the recovery ratio to the straight wire and its effectiveness parameter. The recovery ratio is less than zero that means the friction force affected the shape recovery of the SMA wires in the tube. Even though the effectiveness is greater than 1, which means the spiral configuration is always better performance as the view point of the saving space for the locating long SMA wires in the morphing wing Figure 7 shows the recovery rate vs wrapping angle.

Table 2: Four different settings of the spiral parameters.

Radius R (mm)	**Spiral angle θ (degree)**	**Wraping angle ϕ (deg)**	**Spiral length (mm)**	**Storage ratio β (Spiral length/Height)**
15.0	14.5	720	194.7	4.0
15.0	14.5	1080	292.0	4.0
15.0	14.5	1440	389.4	4.0
15.0	14.5	1800	486.7	4.0

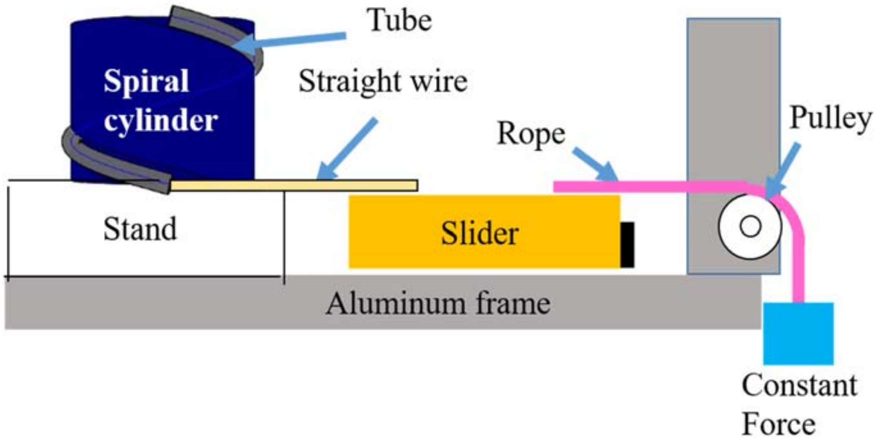


Figure 5: Spiral part and straight part of the SMA wire.

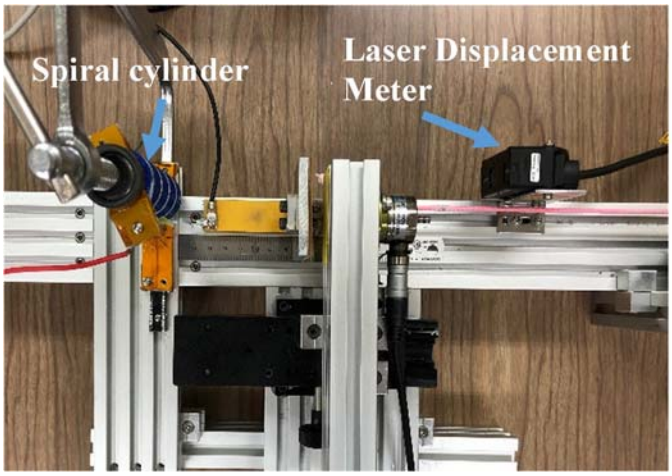


Figure 6: Experimental setup.

Table 3: Results of the recovery experiments of the SMA wires: the effectiveness is defined as the ratio between the length of the spiral cylinder and the actual length of the installed SMA wires.

Wrapping angle ϕ (deg)	**Effective recovery rate γ (Spiral recovery ratio/Straight recovery ratio)**		**Effectiveness of spiral cylinder $\beta \times \gamma$**	
	3N	**6N**	**3N**	**6N**
720	0.97	0.72	3.9	2.9
1080	0.91	0.80	3.7	3.2
1440	0.85	0.69	3.4	2.7
1800		0.50		2.0

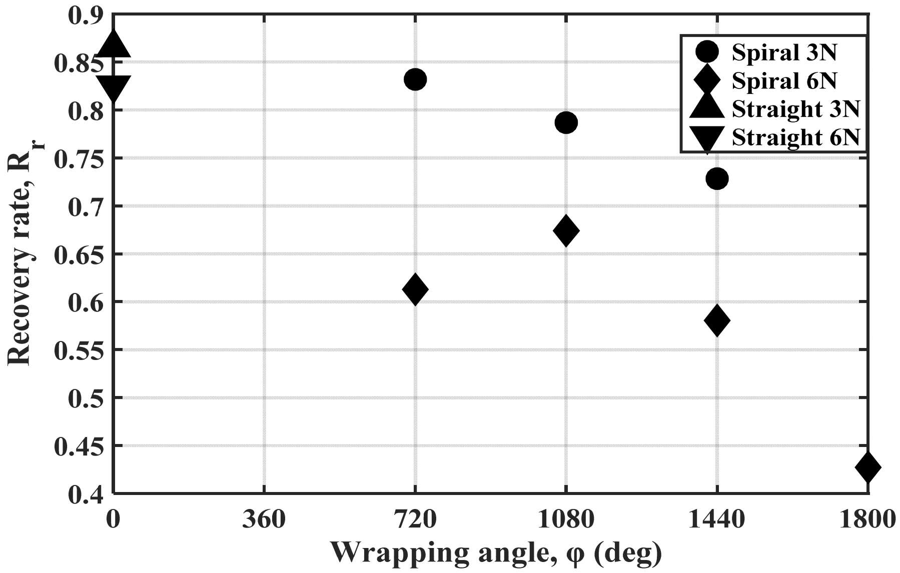


Figure 7: The recovery rate vs. the wrapping angle for the two different constant forces, 3N and 6N.

Table 4: Theoretical estimation on the effect of the friction force. The modified Euler belt theory and its original one were applied to calculate the friction force.

Wrapping angle ϕ (deg)	$\frac{T}{T_0} = e^{\frac{\varphi\mu R}{\sqrt{R^2+\left(\frac{H}{2\pi}\right)^2}}}$	$\frac{T}{T_o} = e^{\mu\varphi}$
720	11.3	12.3
1080	38.2	43.1
1440	128.8	151.0
1800	433.9	529.5

Table 4 shows the theoretical values of the force ratio between the constant force and required force for the actuation. For example, when the wrapping angle is 720 deg and the constant force is 6N, then the recovery force of the SMA wire must be greater than 67.8N. However, the tensile test of the SMA wire used in this experiment showed the recovery force was 35N, which is about 50% of the 67.8N. This indicated that the actual friction force is much less than the theoretical estimation. It is assumed that the actual wrapping angle is less than assumed value shown in Table 4.

3. Conclusions

The spirally arranged SMA wires were investigated to save the space for locating longer SMA wires that are necessary for the large actuation stroke. However, the friction between the wires and spiral guide tube cannot be neglected and must be understood in detail to design the actuator. We conducted two experiments on the limitation of the spiral arrangement of the SMA wires. The first experiment showed the validity of the basic actuator performance. Then, the second experiments showed the limitations of the spiral configuration due to the increment of the friction force between the SMA wire and the guide tube surface. Although the recovery strain gradually decreased as the wrapping angle of the SMA wire increased, the advantage of the spiral arrangement was confirmed.

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