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SHAPE MEMORY ALLOY ACTUATOR PROTECTED BY ROLLED FILM TUBE FOR ARTIFICIAL MUSCLE

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ABSTRACT

In this study we aim to realize an actuator that is comparable with a natural muscle from a viewpoint of flexibility, the output force and the responses. We constructed the Shape Memory Alloy (SMA) coil actuator protected by “a rolled film tube” with the high heat resistance and the high flexibility, and it is named “the unit cell”. The SMA coil in the unit cell is cooled down by inert liquid flowing through the rolled film tube. Then we constructed an actuator named “a motor unit” with the larger output force by bunching up seven unit cells, and the characteristics of the motor unit are investigated by the experiments in which the motor unit is driven in Pulse Frequency Modulation (PFM) found in the bio-motion. The result of the experiments shows that the static characteristics of the output force and the displacement to the input pulse frequency in the motor unit near proportion relations in comparison with the unit cell still more and the output force increases almost seven times as large as the unit cell. Consequently, it is found that these actuators proposed can be employed as applications to a flow control valve and an artificial arm.

KEY WORDS

Shape Memory Alloy, Artificial Muscle, Rolled Film Tube, Motor Unit, Pulse Frequency Modulation

NOMENCLATURE

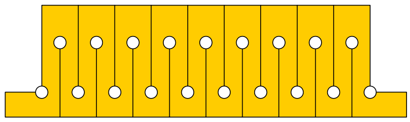
g	:	gravity acceleration	9.8m/s^2
L	:	output displacement in steady state	m
m	:	mass of weight	kg
P	:	input power	W
T	:	time constant	s
η	:	power efficiency	%

INTRODUCTION

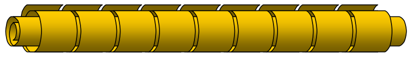
Recently, the necessity for a robot with high affinity for human is increasing. Such a robot needs artificial muscles with the figure and flexibility like those of a human body. Shape Memory Alloy (SMA) actuators with strong output force and large output displacement are researched as artificial muscle actuator in many research institutions. Thin SMA wires with small heat capacity are bunched in parallel at high density in order to get a high response and a strong output force. However, the bunched thin SMA wires are not able to bend with flexibility. And the heat is accumulated in the space around the bunched thin SMA wires, so the compulsion cooling is necessary. A SMA wire is inserted in a high flexibility tube, and its some tubes are bunched. These SMA wires inserted are cooled by coolant flowing through the tubes. However, there have been no tubes that can fulfill two requirements of high heat resistance and high flexibility so far. For the solution of the above problem in this study [1], firstly, "a rolled film tube" with high heat resistance and high flexibility is proposed as a machine element for SMA actuators. Secondly, "a unit cell" is constructed with a SMA wire inserted in a rolled film tube as a minimum unit of artificial muscle. Thirdly, "a motor unit" like a natural muscle of spindle shape is constructed with a bunch of unit cells. An artificial arm should be driven by natural nerve impulse. The characteristics of the motor unit driven are investigated by the experiment in PFM. The pulse width and pulse frequency band of PFM are the same as a natural nerve impulse. Consequently, the output force and the output displacement are acquired which is almost in proportion to the pulse frequency. It is found in this study that the influence on the time constants of step response against input pulse frequency can be decreased by the pulse width control, and now the power conversion efficiency is several % [1].

CONSTRUCTION OF MOTOR UNIT

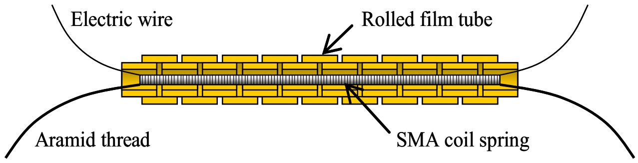
On the anatomy, a bunch of muscle cells controlled by one motor nerve is called "a motor unit" [2]-[4]. "A unit cell" corresponds to one natural muscle cell. So in this study, a bunch of unit cells is called "a motor unit". How to make "a unit cell" is shown to the following. A film is cut as shown in Figure 1 (a). "A rolled film tube" is made of the film rolled as shown in Figure 1 (b). A rolled film tube is made of polyimide that has high heat resistance with glass transition point higher than 500℃. And a rolled film tube has a slide structure that can hold efficiently large displacement inner, so it acquires eminently large compliance as shown in Figure 2. Figure 2 shows the characteristics of a rolled film tube, and the characteristics of a silicone rubber tube are shown in this figure for comparison. Two electric wires and two aramid threads are attached on the both ends of a coil spring made of a thin SMA wire, and its SMA coil spring is inserted into the rolled film tube as shown in Figure 1 (c). Figure 1(d) shows that "a motor unit" is bunched by unit cells, and two silicone rubber tubes are attached on the both ends of the motor unit. A SMA coil spring in each unit cell bunched as a motor unit is equally cooled by coolant flowing through a rolled film tube. A photograph of the motor unit is shown in Figure 1 (e). Practically, the flow control valve as shown in Figure 3 (a) and the artificial arm as shown in Figure 3 (b) [1] can be realized by using some motor units.



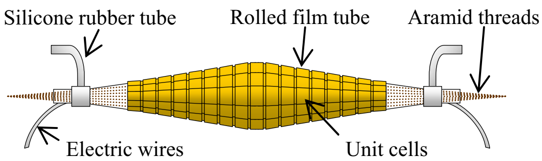
(a) Cut pattern



(b) View of rolled film tube



(c) Inside of unit cell



(d) View of motor unit

(e) Photograph of motor unit

Figure 1 Motor unit

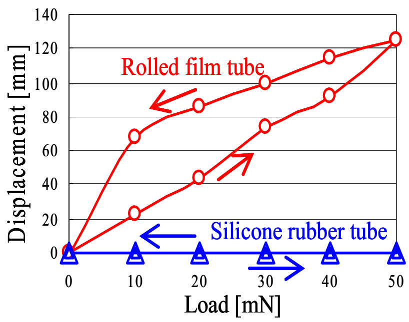
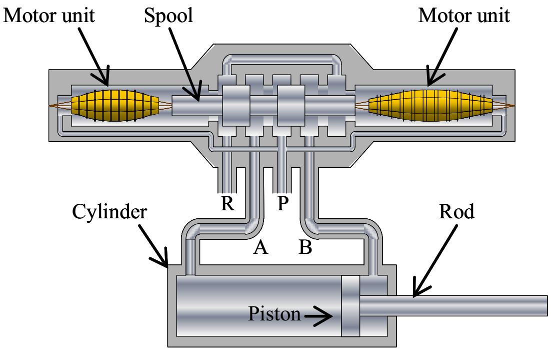


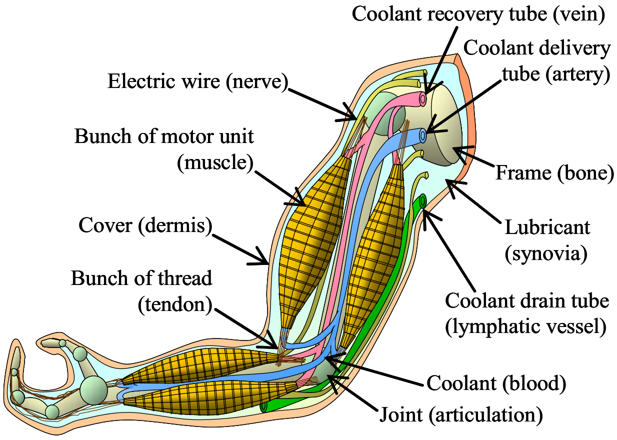
Figure 2 Compliance characteristics

APPARATUS AND METHODS

In this experimental apparatus, Figure 4 (a) shows the front view and Figure 4 (b) shows the side views. The cross section of a motor unit is shown in Figure 5. The specifications of a unit cell are shown in Table 1. For minimizing the volume of a motor unit, 7 unit cells are bunched in a circle with minimum cross section area.

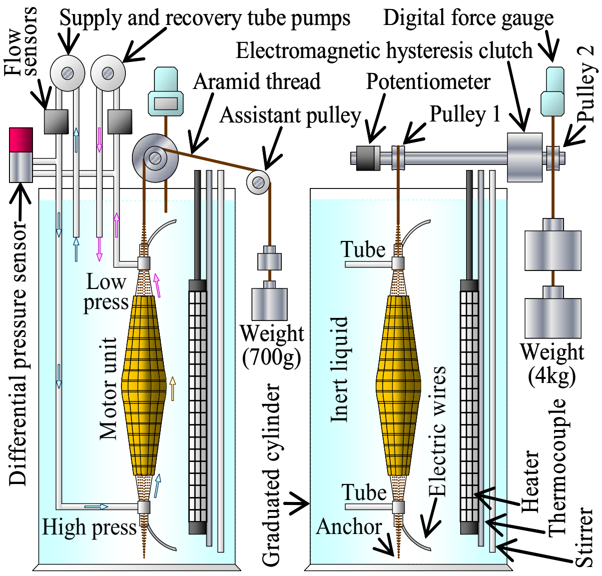


(a) View of flow control valve



(b) View of artificial arm

Figure 3 Applications



(a) Front view (b) Side view

Figure 4 Experimental apparatus

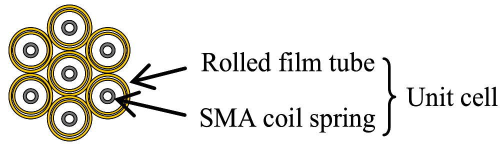


Figure 5 Cross section of motor unit

Table 1 Specifications of unit cell

Rolled film tube	Outer diameter [mm]	ϕ1.5
	Length [mm]	100
SMA coil spring	Coil outer diameter [mm]	ϕ0.6
	SMA wire diameter [mm]	ϕ0.2
	Length [mm]	80
	Phase transformation temperature [℃]	60
Weight [g]		0.15

Table 2 Specifications of inert liquid

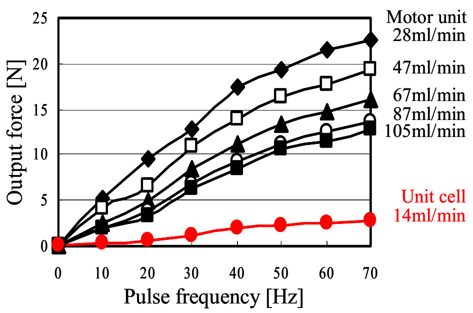
Hydrofluoropolyether (HFPE)	
Boiling point [℃]	178
Density [kg/m³]	1720
Specific heat [J/(kg·K)]	1092
Thermal conductivity [W/m·K]	0. 087

Its total weight is 1.05g. The coolant used is an inert liquid with electric high insulation. Its coolant is flowed by the supply and recovery pumps from the bottom of a motor unit to the top, and its temperature is kept to 36℃ by the temperature controller constructed with a heater, a thermocouple and a stirrer. The specifications of an inert liquid as coolant are shown in Table 2. The thread on the top of a motor unit is twisted around the pulley 1 clockwise once, and its end is pulled by the weight of 7N (700g). The output displacement of a motor unit is measured by the angles of the potentiometer. The pulley 1 and 2 are separated or connected by the electromagnetic hysteresis clutch. While, one thick thread is twisted around the pulley 2 clockwise once. The upper end of its thread pulls the digital force gauge and its lower end is pulled by the weight of 40N (4kg). Therefore, the pulley 2 is held by the brake torque of 40Ncm. At this time, the weight of 40N is indicated by the digital force gage. For measurement of the output force, first, the pulley 1 and 2 are separated, then a motor unit is given a bias strain by the weight of 7N (700g) as shown in Figure 4. Next, the pulley 1 and 2 are connected, and then the SMA coil springs in a motor unit are heated by electric heating. Though a motor unit contracts, the pulley 1 is kept initial position by the pulley 2 braked. Then the weight of less than 40N is indicated by the digital force gage. The difference between its weight and 40N is the output force of a motor unit.

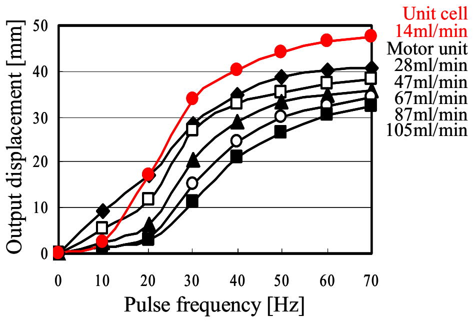
RESULTS AND DISCUSSION

Output force and output displacement

It is found on the experiments that if the constant frequency pulse voltage is supplied to a motor unit, the static constant output force and the output displacement are generated corresponding with its frequency. Above result is confirmed on the rehearsal experiments [5]. Therefore, the constant frequency voltage pulse trains are supplied to a motor unit. The pulse width (0.5ms) and frequency band (10-70Hz) of its pulse train are same as a natural nerve pulse train. Then the output force and displacement generated is measured about every frequency. The height of pulse voltage is 100V which is the rated voltage of a switch device. The relations of output force and output displacement of motor unit against pulse frequency are shown in Figure 6 (a) and 6 (b), respectively. For comparison, the experimental result of one unit cell is inserted into Figure 6 (a) and 6 (b). Figure 6 shows that the maximum output force of the motor unit is 22.5N, and amounts to 7 times of a unit cell. The maximum output displacement is 40.6mm. Consequently, when a motor unit is made of seven unit cells bunched, its output force is seven times bigger than one unit cell's output force and its output displacement is 85% of one unit cell's output displacement. It is found that the output force of a motor unit increases in proportion with number of the unit cell, and the reduction of the output displacement is due to the friction between the bunched unit cells.



(a) Output force



(b) Output displacement

Figure 6 Static characteristics of motor unit

Pulse frequency and step response

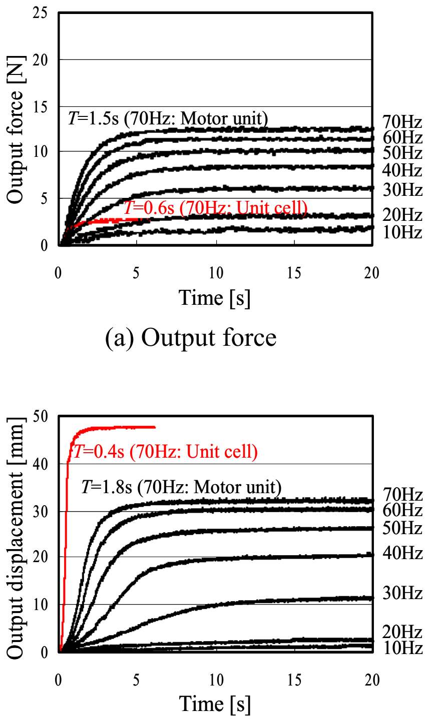
The step responses of the motor unit are obtained experimentally on the coolant flow of constant 105ml/min. These results are shown in Figure 7 (a) and 7 (b). For comparison, the results of response of the output force and the output displacement of one unit cell are inserted into Figure 7 (a) and 7 (b). The experimental condition are as follows, (coolant flow: 14ml/min, pulse width: 0.5ms, pulse frequency: 70Hz). When the pulse voltage trains (height: 100V, width: 0.5ms, frequency: 10-70Hz) are inputted to a motor unit and a unit cell at the zero second, Figure 7 (a) and 7 (b) show the temporal responses of output force and output displacement on a motor unit and a unit cell. Figure 7 shows that the time constant T of the output force is 0.6s and the time constant T of the output displacement is 0.4s. However, on the pulse frequency of 70Hz, the minimum time constant T of a motor unit is 1.5s on the output force and is 1.8s on the output displacement. Consequently, the time constants of one motor unit are 2.5 times of the unit cell about output force, and are 4.5 times of the unit cell about output displacement.

Pulse width and step response

The heat capacity of the motor unit increases, because the dead space volumes of a motor unit increase by bunching unit cells as shown in Figure 5. It is considered that the increase of the time constant depends on the increase of the heat capacitance of the motor unit. At the pulse frequency of 70Hz, the step responses of the output force and the output displacement are shown in Figure 8 (a) and 8 (b), by taking pulse widths as parameter. The pulse width patterns of the pulse trains are shown in Figure 9. The time constant T in the step response about the output force of the motor unit is 1.5s, when the pulse width is 0.5ms. Its time constant is 0.9s longer than the time constant of 0.6s of a unit cell. When the pulse width is extended to 2.0ms, the time constant T is shortened to 0.8sec. Similarly, the time constant T in the step response about the output displacement of a motor unit is 1.8sec, when the pulse width is 0.5ms. Its time constant is 1.4sec longer than the time constant of 0.4sec of a unit cell. When its pulse width is extended to 2.0ms, the time constant T is shortened to 0.5s. Therefore, when the pulse width of a motor unit is extended, its time constant is shortened to the level of a unit cell.

Pulse frequency and time constant

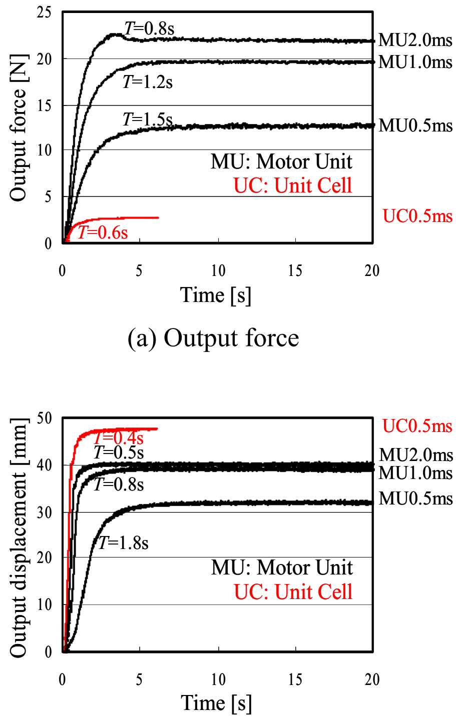
The time constants of the output force and the output displacement against the pulse frequencies are shown in Figure 10 (a) and 10 (b). In Figure 10, the time constants are not mostly influenced by the frequency higher than 40Hz in case of the pulse width more than 1.0ms. Consequently, it is found that the influence of the frequency on the time constant can be made smaller by controlling the pulse width.



(a) Output force

(b) Output displacement

Figure 7 Pulse frequency dependency on step response



(a) Output force

(b) Output displacement

Figure 8 Pulse width dependency on step response

Pulse frequency and power efficiency

The power efficiencies of the actuator in this study against the pulse frequencies by the pulse widths as the parameters are shown in Figure 11, by taking the pulse widths as parameter. The power efficiency η [%] can be obtained by the following equation.

$$\eta = \frac{mg \cdot (0.63L/T)}{P} \times 100$$

In this equation, $0.63L/T$ is the average velocity [m/s] of a unit cell or a motor unit. In Figure 11, the power efficiency of a unit cell shows approximately 9% in the frequency region higher than 30Hz. It is well-known that the power efficiency of SMA is approximately 10% [6], and the efficiency of our unit cell attains to this value. However, the power efficiencies of a motor unit show several % in the frequency region higher than 20Hz.

Comparison of natural muscle with motor unit

The main data of a natural muscle and a motor unit are shown in Table 3. The data of a natural muscle are calculated by using the reference [2]-[4]. The size of the natural muscle model is set at the same size with a motor unit.

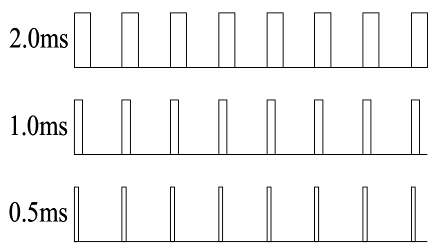
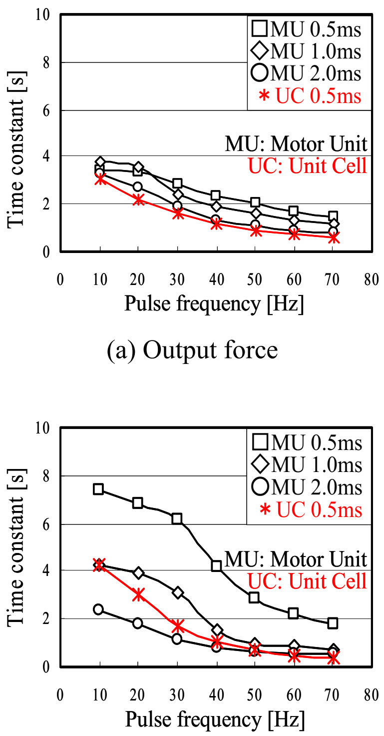


Figure 9 Pulse width pattern

The outer diameter is φ4.5mm, the length is 100mm, and the volume is 1590mm^3. In summary of Table 3, the weight and the density are approximately half on a motor unit against a natural muscle model. The maximum output force and the maximum output pressure are approximately 3 times. The maximum output displacement is approximately same. The maximum output force/self weight and the maximum output pressure/density are approximately 4 times [7]. From these results, it is found that the characteristics of a motor unit in this study are more excellent than a natural muscle. From this study, it is found that the time constant can be improved by controlling the pulse width to some extents.



(a) Output force

(b) Output displacement

Figure 10 Pulse frequency dependency on time constant

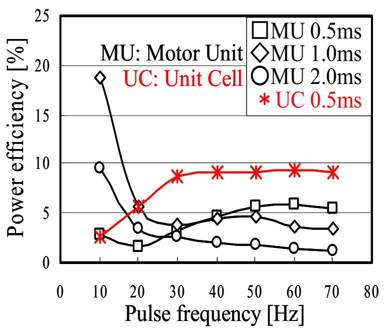


Figure 11 Power efficiency characteristics

Table 3 Comparison of natural muscle with motor unit

Item	Natural muscle	Motor unit
Diameter [mm]	ϕ4.5	
Length [mm]	100	
Volume [mm^3]	1590	
Blood temperature [℃]	36	
Impulse width [ms]	0.5	2.0
Weight [g]	1.63	1.05
Density [kg/m^3]	1020	660
Maximum output force [N]	7.95	21.9
Maximum output displacement [%]	50.0	40.5
Minimum time constant of output force [ms]	40	800
Maximum output pressure [MPa]	0.50	1.38
Maximum output force / weight	497	2127
Maximum output pressure / density [kPa･m^3/kg]	0.49	2.09

CONCLUSIONS

"A rolled film tube" with high heat resistance and high flexibility is proposed. "A unit cell" as minimum unit of the artificial muscle is constructed with a rolled film tube and a SMA coil spring. A SMA coil spring inserted into "a unit cell" is cooled by the inert liquid through the rolled film tube. "A motor unit" is constructed with a bunch of 7 unit cells. The characteristics of a motor unit are investigated experimentally. The main results are as follows.

(1) The static characteristics of the output force and the output displacement are approached to the static characteristics of a living body by bunching unit cells.

(2) In the same frequency, the input heat quantity can be controlled by the pulse width.

(3) When the pulse width is expanded, the power efficiency is decreased in the high frequency band.

It is found that a motor unit may be able to drive directly by a natural nerve impulse. The construction of the control system with higher power efficiency and smaller time constant will be an aim of our further study.

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