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Design parametric study based fabrication and evaluation of in-pipe moving mechanism using shape memory alloy actuators

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Abstract

An in-pipe moving mechanism based on design parametric study of dynamic characteristics of clamping or moving module comprising shape memory alloy (SMA) spring actuators has been fabricated and evaluated under in-pipe condition. Conventional in-pipe moving mechanisms for pipe inspection, driven by electromagnetic motors, have large volume and mass. The SMA actuator can be an alternative for a small-sized in-pipe moving mechanism due to its great power-to-weight ratio and simple structure. Therefore, spring type SMA actuators are selected to fabricate an inchworm-like moving mechanism that consists of clamping and moving modules. For selection of proper operating type (a bias type or a differential type) for clamping module and moving module, displacements and dynamic characteristics of each operating type have been investigated. Based on experimental results, we decide some design parameters such as wire diameters, spring diameters and the numbers of turns of SMA spring actuators and fabricate the in-pipe moving mechanism according to the designed results. A moving speed of 34 mm/min and traction force of 0.4 N have been obtained from the driving experiment in a pipe with the diameter of 39 mm.

Keywords: Shape memory alloy; In-pipe moving mechanism; Bias-type actuator; Differential-type actuator

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1. Introduction

The development of modern industries has brought about complex machines and devices and they require small-sized in-pipe moving mechanisms for inspection and repair. Since large-sized in-pipe moving mechanisms [1] using conventional motors are not suitable for the inspection of complex devices, research on micro in-pipe moving mechanisms using micro motors [2, 3] and smart material based actuators such as piezo [4, 5], and SMA (shape memory alloy) actuators [6, 7] has been carried out. In addition, micro pneumatic actuators based in-pipe moving mechanisms are also actively studied due to their flexibility, compactness and high generative force [8, 9].

In this paper, an inchworm-like in-pipe moving mechanism based on design parametric study of SMA spring actuators is fabricated and tested under in-pipe condition. In order to choose a proper operating type for each module (clamping or moving module) of

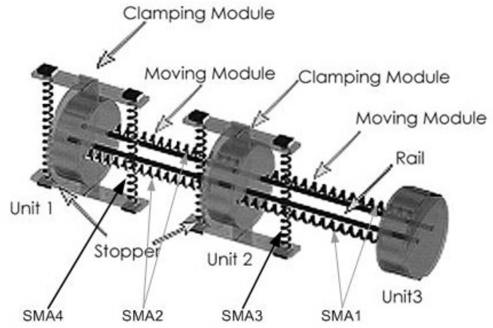

Fig. 1. Structure of in-pipe moving mechanism.

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inchworm-like moving mechanism, displacement and dynamic characteristics of each operating type (a bias type or a differential type) are tested. Based on experimental results, a bias type SMA actuator is utilized for clamping modules of an in-pipe moving mechanism.

For moving modules, the appropriate structure design of a SMA spring actuator and the optimum driving condition are determined by investigating the dynamic characteristics of a differential type SMA actuator. Based on the measured dynamic characteristics and optimized design parameters such as wire diameters, spring diameters and the numbers of turns, the in-pipe moving mechanism is fabricated and tested with the optimum driving condition under in-pipe condition.

2. Overall design and principles of motion

An inchworm-like motion is selected for designing the in-pipe moving mechanism. It consists of clamping modules that are used to fix the in-pipe moving mechanism to the pipe wall and moving modules that generate motion. When it comes to actuation of the moving modules and the clamping modules by using SMA actuators, a bias type or a differential type design method can be considered. The bias type actuation using a spring-type SMA actuator combined with a bias spring has one-way motion, whereas the differential type actuation replaces the bias spring with an SMA spring actuator for two-way motion.

Fig. 1 shows the designed in-pipe moving mechanism that consists of eight SMA spring actuators by adopting differential type actuation for both the moving modules and the clamping modules. Among the eight SMA actuators, four of them are used for the clamping mechanism to the pipe wall and the other four actuators are used for the moving modules. Unit 1 and Unit 3 are fixed to the ends of the rails whereas Unit 2 is free to move along the rails as shown in Fig 1. A miniature CCD camera is attached to Unit 3 for inspection within the pipe. Each stopper is attached to Unit 1 and Unit 2 in order for only one module at a time, either Unit 1 or Unit 2, to support the pipe wall. Forward motion takes place once as it undergoes the four-step process by adopting the principles of motion of an inchworm, as shown in Fig. 2. When the current flows through SMA 4, the SMA spring in Unit 2 does not contract due to the stopper and the one in Unit 1 supports the pipe wall (a). Unit 2 moves to the right as the current is applied to SMA 1 (b). At this moment, applying the current to SMA 3 after disconnecting the current in SMA 1 and SMA 4 causes Unit 2 to support the pipe wall (c). Now, by applying the current to SMA 2, the whole in-pipe moving mechanism except for Unit 2 supporting the pipe wall moves to the right (d). Consequently, the in-pipe moving mechanism moves forward as it repeats the four-step process and it can accomplish backward motion as the order of applying the current to SMA 1 and SMA 2 is reversed.

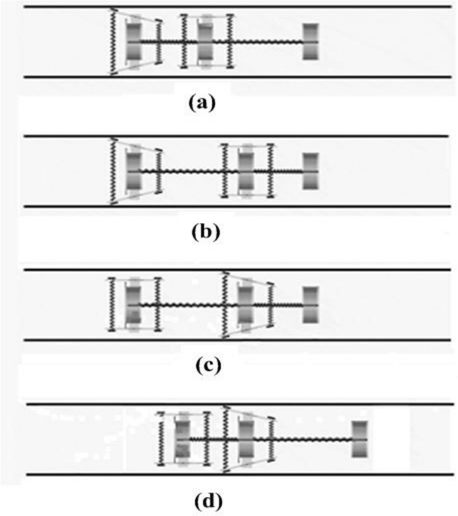


Fig. 2. Working Principle of In-pipe Moving Mechanism.

3. Determining actuation type for clamping and moving modules

Characteristics of a SMA actuator vary according to the design of a SMA spring actuator and its operating type. Consequently, suitable operating types for the clamping modules and the moving modules of the in-pipe moving mechanism should be selected between the bias type and the differential type. The adequate design parameters (wire diameter, spring diameter and number of turns) of a SMA spring should also be determined. Since the moving modules of the in-pipe moving mechanism determine the performance of the whole mechanism, the velocity of the actuator should be fast and the displacement of the actuator should be large. However, when it comes to the clamping part, generated force should be of greater concern than displacement since it has to provide enough force to support the pipe wall. Understanding the operating characteristics and determining the driving conditions for the bias type and the differential type are accomplished by measuring the dynamic characteristics of each actuator's operating type [10].

3.1 Dynamic characteristics of bias-type and differential-type actuators

In this research, dynamic characteristics for the SMA actuator are expressed as displacement according to the frequency of the applied voltage. To measure the dynamic characteristics of the bias type actuator and the differential type actuator, a SMA spring and a bias spring are used. The experimental results are presented in Fig. 3. The differential type generates greater displacement than the bias type when the initial length of each spring is equal. Based on these results, the differential type actuator was selected for the moving module of the moving mechanism that requires large displacement. The bias type actuation was selected for the clamping modules that require large generative force rather than large displacement. This simplifies electric connection of the whole moving mechanism by reducing the number of required SMA actuators.

Consequently, in order to fabricate an efficient moving mechanism, dynamic characteristics and driving conditions for the differential type actuator should be obtained and an accurate design method for the bias type actuators used for clamping modules should be established.

3.2 Designing and driving condition of moving module

In order to obtain dynamic characteristics of the differential type SMA actuator in the variation of design parameters of the SMA spring, the displacement of the actuator was measured according to the frequency of the applied voltage by varying the wire diameter, the spring diameter, and the number of turns. Initial displacement from memorized length is required to obtain specific displacement of the actuator. At that time, keeping constant shear strain is important to guarantee performance of the actuator. Therefore, initial deformation is set to specific displacement as much as the actuator can have constant shear strain even if the spring design varies. Eq. (1) can be used to obtain the initial deformation so that the wire can have constant shear strain regardless of SMA spring structure [11].

$$\delta = \left(1 + \frac{G_L}{G_N}\right)\frac{\pi n D^2 \gamma_L}{2d} \tag{1}$$

In Eq. (1), δ is the initially set displacement of the SMA spring, G_H and G_L are the shear moduli at high and low temperatures, respectively, d is the wire diameter, D is the spring diameter, n is the number of turns, and γ_L is the shear strain at low temperature. The measured results of the dynamic characteristics obtained by setting γ_L to 2 % are shown from Fig. 4 to Fig. 8. The moving module should generate enough force to move the moving mechanism itself and the CCD camera attached to it. Since the weights of the moving mechanism and the commercially available CCD camera are 14 g and 28 g respectively, a force of approximately 0.4 N is necessary for the moving modules to drive the moving mechanism. Each module of the moving mechanism utilizes two SMA springs as shown in Fig. 1. Therefore, each spring should generate a force greater than 0.2 N.

The maximum shear strain, γ_L, is set to 2 % since reliability and fatigue failure of the spring type SMA

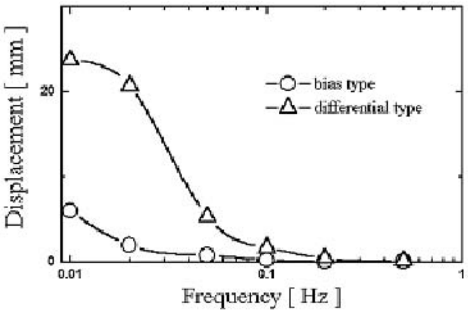


Fig. 3. Frequency Characteristics of Bias Type and Differential Type SMA Actuators (Actuator Parameters in Table 2 are utilized).

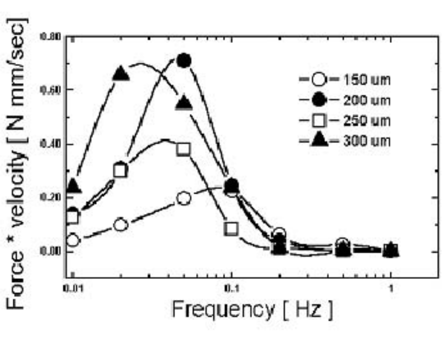


Fig. 4. Response of Power under Variation of Wire Diameter and Frequency of Applied Voltage (D: 1.5 mm, n: 20 turns).

actuators are taken into account. In general, reliability and fatigue failure of SMA actuators are well known by many researchers, and it is reported that they vary according to an allowable load and strain [12-13]. It is also reported that the maximum shear strain should be set to less than 2 % in case reliability (the number of shape recovery>10^4) is of greater concern than large displacement or generative force. In this research γ_L was also set to 2 % in order to minimize the deterioration of the SMA actuators due to their repeated motion. In fact, the designed SMA actuators using the method previously mentioned were found to show no change in the characteristics of the actuators after several hundreds of repeated experiments.

The product of force and velocity is defined as power output to determine the diameter of the wire. The variations of power output, force, and velocity are measured by varying the diameter of the wire. In Fig. 4, greater power outputs are obtained with the wire diameters of 200 μm and 300 μm. Both 200 μm and 300 μm of the wire diameters satisfy the requirement for a generative force greater than 0.2 N, as shown in Fig. 5. Between the two wire diameters, a wire diameter of 200 μm is selected since it provides a faster velocity as shown in Fig. 6. As we can expect, the generative force increases as the wire diameter increases, whereas the velocity decreases as the ratio of the volume to the surface area decreases. The wire diameters of 250 μm and 300 μm provide similar results in Fig. 6. This can be explained by the fact that there is almost no difference in cooling effect for both cases. From these results, it can be interpreted that the product of force and velocity from Fig. 4 does not have any certain trend according to different wire diameters. However, the most suitable design and driving condition can be clearly determined in terms of the maximum power output as shown in Fig. 4.

With the same method that was previously carried

Table 1. Designed values of SMA springs for moving module.

Spring Design	Designed Value
Wire Diameter (μm)	200
Spring Diameter (mm)	1.5
Number of Turns (turns)	30

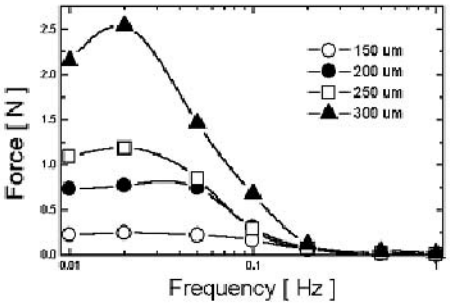


Fig. 5. Frequency response of force under variation of wire diameter (D: 1.5 mm, n: 20 turns).

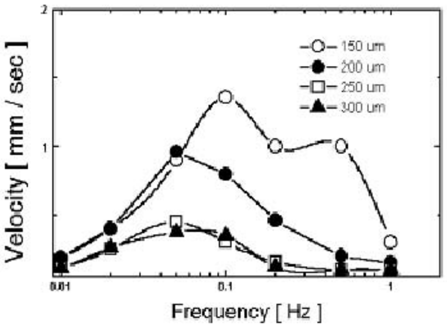


Fig. 6. Frequency response of velocity under variation of wire diameter. (D: 1.5 mm, n: 20 turns)

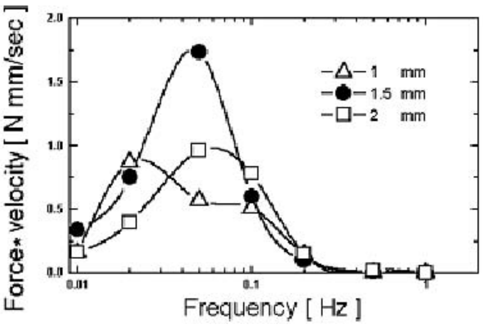


Fig. 7. Frequency Response of Power under Variation of Spring Diameter (d: 200 μm, n: 20 turns).

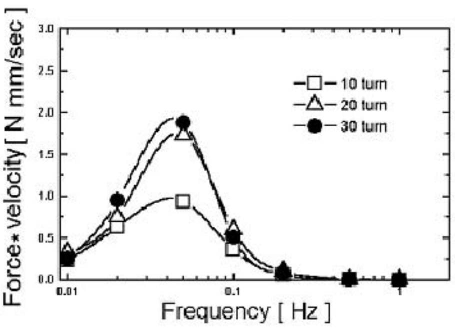


Fig. 8. Frequency Response of Power under Variation of Number of Turns (d: 200 μm, D: 1.5 mm).

out in determining the wire diameter, 1.5 mm of the spring diameter that maximizes the product of force and velocity as shown in Fig. 7 is selected. The power output according to the number of turns is presented in Fig. 8. Based on those experimental results, 30 turns of the SMA springs that maximizes the power output is selected for the moving modules. The design parameters of the SMA springs for the moving modules are arranged in Table 1. The driving frequency which generates the maximum power output, the product of force and velocity of the SMA spring with the designed parameters given in Table 1, is found to be 0.05 Hz from the experimental results of the dynamic characteristics in Figs. 4, 7, and 8. Consequently, it can be concluded that the optimum driving frequency of the moving modules that maximizes force and velocity is 0.05 Hz.

3.3 Designing clamping module

It is necessary to establish a proper design method for a bias type SMA actuator since the clamping modules of the moving mechanism utilizes bias springs. The design process for the bias type actuator is to find design parameters of the SMA spring and the bias spring to generate necessary force and displacement for the desired operation. Appropriately finding design parameters involves determining the wire diameters, the spring diameters, the numbers of turns, and the initial lengths of SMA and bias springs [14]. The necessary force for the moving modules should be greater than 0.4 N as explained in section 3. In addition, the clamping modules should generate enough force to support the pipe wall preventing slippage of the moving mechanism while the moving module is in operation. Therefore, their relationship can be expressed as follows:

Table 2. Designed values and fabricated values of SMA and bias springs for clamping module.

	Spring Design	Designed Value	Fabricated Value
SMA Spring	Wire Diameter (μm)	254	254
	Spring Diameter (mm)	1.15	1.2
	Number of Turns (turns)	39	39
Bias Spring	Wire Diameter (μm)	0.5	0.5
	Spring Diameter (mm)	5.6	6
	Number of Turns (turns)	44	44

Generated Force of Moving module = (Coefficient of Friction between Pipe Wall & clamping module) × (Generated Force of clamping module)

Since the coefficient of friction between the pipe wall and a clamping module was measured to be 0.6, it can be known that the clamping module generates a force of 0.67 N from the relationship mentioned previously. With the clamping module's generated force of 0.67 N and 2 mm of the generated displacement, the bias type SMA actuator was designed as in reference [12]. The designed values and the fabricated values of an SMA spring and a bias spring for the clamping modules are summarized in Table 2.

The SMA and the bias springs are fabricated with the values given in Table 2 and they are assembled as shown in Fig. 10. Then, the generative force and the displacement are measured. The measured values of the generative force are in good agreement with the designed values as shown in Fig. 9, but the measured values of the displacement are not quite in agreement with the designed values. It is thought that the errors might come from the manufacturing process and the frictional force of the supporting part. The SMA springs used are the wires made by Dynalloy Inc. (USA) which are fabricated into the shape of a spring and undergo a heat treatment process whose transformation temperature (A_f) is 70°C.

4. Fabrication of moving mechanism and measured results

The moving mechanism was manufactured after combining the moving modules fabricated by using the designed differential actuator with the clamping

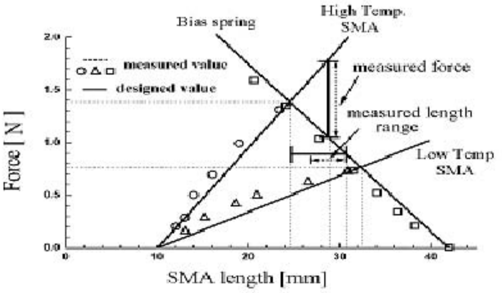


Fig. 9. Designed Values and Measured Results of Supporting Part.

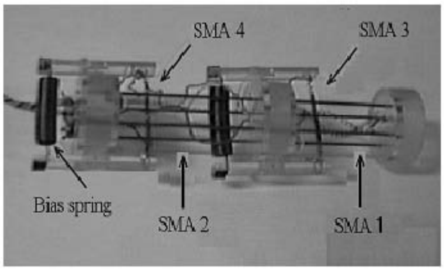
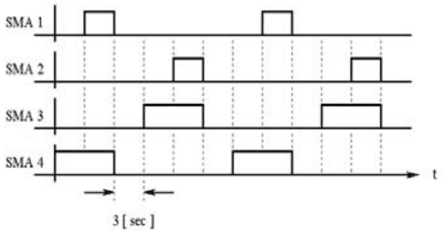
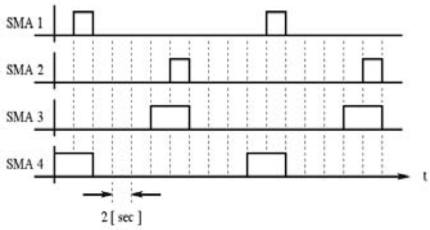


Fig. 10. The fabricated in-pipe moving mechanism.



(a) Optimum driving condition determined by empirical data



(b) Optimum driving condition determined by measured dynamic characteristics

Fig. 11. Optimum Driving Conditions.

parts fabricated by using the proposed bias type actuator. The dimensions of designed moving mechanism are 35 mm in height and 110 mm in length. Fig. 11 shows (a) the best switching waveforms that were obtained empirically based on several hundreds of repeated experiments and (b) the switching waveforms obtained from measuring the dynamic characteristics to secure the optimum driving condition. By operating the moving mechanism with each waveform, we verify the usefulness of the optimum driving condition that is obtained through the dynamic experiment. An I/O board (NI Lab-PC-1200) was used to generate the switching signal as shown in Fig. 11 and LabVIEW was selected for the operating program. The experiment was performed in a glass tube with a diameter of 39 mm. The moving distance was measured with a laser displacement gauge (Keyence LB-70).

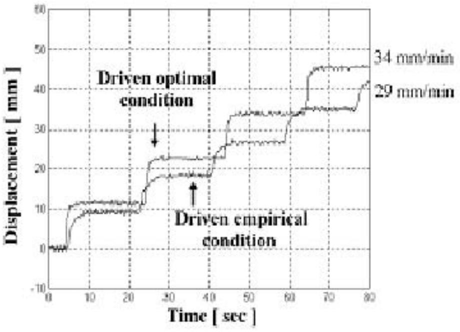


Fig. 12. Moving characteristics of the proposed mechanism under driving conditions obtained from dynamic characteristics and empirical data.

Fig. 12 shows the motions of the moving mechanism that is operated under 0.05 Hz. With the optimum and empirical driving conditions, the velocities of the moving mechanism are 34 mm/min and 29 mm/min, respectively.

5. Conclusion

In this paper, a design method for the in-pipe moving mechanism using the SMA spring type actuator was proposed and the performance of the in-pipe moving mechanism fabricated according to the proposed design method was investigated.

For the moving modules and clamping modules of the in-pipe moving mechanism, the dynamic characteristics of the differential type actuator and the bias type actuator were tested. Based on those experimental results, a differential type actuator for the moving modules and a bias type actuator for the clamping modules were employed since the differential type actuator generates fast velocity and the bias type actuator can supply higher force compared to the differential type. In addition, design parameters such as a wire diameter, a spring diameter and the number of turns for SMA spring type actuator that satisfies the design requirement for a traction force of 0.4 N were obtained. The in-pipe moving mechanism moves with a velocity of 34 mm/min in a pipe with a diameter of 39 mm under horizontal condition. The performance of the moving mechanism fabricated in this research is not so superior to the performance of an in-pipe moving mechanism utilizing a conventional motor. However, it is expected that we can realize an in-pipe moving mechanism that can inspect an in-door water pipe less than 15 mm in diameter with some modification of design parameters.

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