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Design of an impact drive actuator using a shape memory alloy wire

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ABSTRACT

This paper introduces an impact drive mechanism (IDM) that utilizes the rapid contraction property of shape memory alloy (SMA) wire. In this study, possible structures for an SMA-wire-based IDM actuator are investigated, and a prototype actuator comprising a main body, an inertia body, an SMA wire, and a bias spring is developed. To verify the applicability of the prototype actuator as a positioning device, driving experiments were conducted under various conditions. The experimental results demonstrated that the prototype actuator enables bidirectional step-like movement with several step sizes by changing the profile of applied voltage, such as amplitude, duty cycle, and frequency. In addition, we developed PI-controller-based position control systems by using these three parameters as control input; the control characteristics and potential applications of each method were discussed. These results implied that the SMA-wire-based IDM actuator has the potential to be used as a new linear actuator in sub-millimeter order driving.

1. Introduction

In recent years, technological advancements have accelerated the trend of downsizing of electrical products. In particular, mobile phones have undergone rapid downsizing, which nowadays support several functions such as high-resolution imaging and high-speed wireless communication. For developing compact products with multiple functions, a compact high-performance actuator that can be driven in the limited space should be one of the most essential components. Electromagnetic motors have been widely used in actuators because of their high performance, easy availability, and good controllability. However, the structure consisting of magnets and coils prevents further size reduction. Currently, the world's smallest commercialized motor has 2 mm in diameter and 5 mm in length [1]. Thus, the application of electromagnetic motors is becoming increasingly difficult as electrical products are downsized. Hence, alternative actuators that are smaller but offer high actuation performance will be necessary in the near future.

Solid-state actuators have been also studied with the aim of realizing smaller and high-power actuators. Solid-state actuators use active materials that generate micro displacement (or strain) under the effect of external energy such as electrical energy elements. Materials commonly used in solid-state actuators are piezoelectric elements, magnetostrictive materials, and shape memory alloys (SMAs), etc. Among these materials, the piezoelectric actuator has particularly attracted our interest owing to its large generative force, precise sub-micron displacement, and fast responsiveness [2]. Hence, various types of actuators based on these properties have been proposed for application to various fields [3–9]. For example, impact drive mechanism (IDM) actuators, which are well known as precise positioning devices that utilize the impact (inertia) and friction force produced when the piezoelectric element is rapidly deformed [3], have been studied for application to scanning tunneling microscopes [4] and cell micromanipulators [5]. Further, Yoshida et al. [6] proposed smooth impact drive mechanism (SIDM) actuator by improving upon the IDM principle. Currently, SIDM actuators are implemented in digital cameras to facilitate auto focus, zoom, and image stabilization. The present study also focuses on the IDM because the application of the driving principle could be very useful in implementing actuation in limited space.

The IDM mainly utilizes the fundamental physical phenomenon that movement of an object accelerated on a friction surface by external impact force stops due to the friction force between the object and friction surface. In previous studies, various types of actuators utilizing the impulsive force have been developed, in which the impulsive force was mainly generated by electromagnetic force [10], inertia force caused by rapid deformations of the piezoelectric element or magnetostrictive material [3,11], air pressures [12], and thermal expansions [13,14]. However, IDM actuators that can offer better performance than piezo-based IDM

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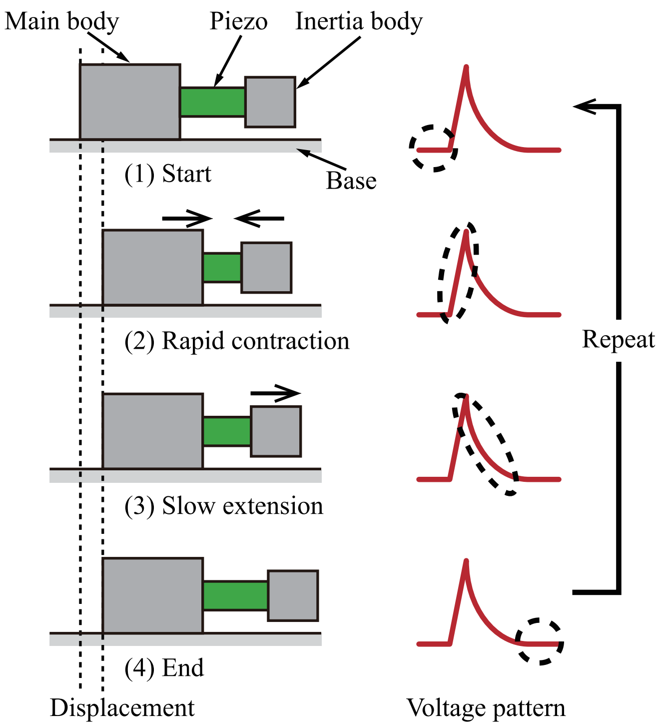

Fig. 1. Driving principle of impact drive mechanism [3]. As an example, the illustration uses a piezo-based IDM actuator to explain the behavior in each step.

actuator have not been developed so far. Thus, this study examines the possibility of using an SMA as the driving source in an IDM. SMAs can be restored to a predetermined shape by Joule heating [15]. The possible strain and generative stress of an SMA are obviously larger than those of a piezoelectric element and magnetostrictive material [16], although the responsiveness is not so high (basically, the SMA is actuated less than 100 Hz [17]). Since SMAs possess excellent energy density and tolerability for galling and corrosion, SMA-based actuators can potentially be applied in various environments. In this study, an IDM actuator using an SMA wire is proposed, and a prototype device is developed to examine whether the proposed actuator performs the expected movement [18]. This paper mainly discusses the possibility of the SMA-wire-based IDM actuator, investigating the basic performance and characteristics of the prototype actuator. In addition, with a view to enabling the practical application of the proposed actuator, we attempt to propose position control methods based on the characteristics of the proposed actuator.

2. Impact drive mechanism

In this section, we introduce the basic principle of IDM to roughly grasp the behavior of an IDM actuator with an SMA wire; here, we take a piezo-based IDM actuator as an example. Fig. 1 shows the schematic diagram of a typical piezo-based IDM actuator. The IDM actuator is mainly composed of three components: a main body in contact with a base, a piezoelectric element to produce the impulsive force, and an inertia body for causing the impulsive inertia force to the main body. Fig. 1 also illustrates the driving principle and the process sequence is as follows:

(1) In the initial state, the main body remains stationary condition on the base.
(2) The inertia body experiences high acceleration toward the main body when the piezoelectric element is activated so as to rapidly contract, inducing an impulsive inertia force on the main body. At this time, the main body slips slightly toward the inertia body if the inertia force exceeds the static friction force between the main body and the base.
(3) The piezoelectric element is activated to gradually extend until the original length, keeping the inertia force below the static friction force; the main body never moves in this period.
(4) Finally, the IDM actuator returns to initial state (1) with a small drift toward the inertia body.

The process described in (1) to (4) produces a tiny step-like displacement toward the inertia body. The step size depends on the friction and the impact force, which is equal to the inertia force generated by the deformation of the piezoelectric element. By repeating this process, the IDM actuator achieves linear movement consisting of continuous step-like displacements. Additionally, the IDM actuator enables the movement in the opposite direction by inverting the contraction and extension speeds of the piezoelectric element.

As shown in Fig. 1, it should be noted that the coupled action of rapid contraction and gradual extension (or rapid extension and gradual contraction) is necessary for the IDM. With regard to the application of an SMA wire to the IDM, rapid contraction can be obtained by intensive heating of the SMA wire, and natural cooling due to the air after the heating could realize gradual extension. Thus, the piezoelectric element can be replaced with an SMA wire in the structure shown in Fig. 1 and an SMA-wire-based IDM actuator would be feasible. However, the rapid extension cannot be realized by the natural air cooling because the cooling speed is not enough; the use of other cooling sources such as a Peltier element might allow faster cooling but the structure becomes more complicated and further downsizing would be difficult. Thus, we expect that an IDM actuator using an SMA wire can achieve only one-way movement, i.e., movement toward the inertia body; the present paper defines the direction of this movement as positive direction.

3. IDM actuator using an SMA wire

3.1. Design

In general, the application of bias force is necessary to repeat the contraction and extension of SMA wire; the SMA wire would slack after heating without the bias force. The bias force can be achieved by applying an external force such as gravity, elastic restoring force, or tension of another SMA wire that is activated antagonistically [19]. Using these bias methods, some possible designs (structures) of SMA-wire-based IDM actuator can be devised on the basis of the structures of piezo-based IDM actuator. Fig. 2(a) shows the structure commonly used for the piezo-based IDM actuator, in which a piezoelectric element is replaced with an SMA wire and a bias spring. This structure would allow one-way movement toward the inertia body because the SMA wire cannot extend rapidly as mentioned in the previous section. Hence, a symmetric structure of Fig. 2(b) would be available to achieve bidirectional movement by switching the activation of the two SMA wires although two SMA wires, bias springs, and actuator drivers are necessary. The structure shown in Fig. 2(c) is stable in comparison with the structure of Fig. 2(a). In this structure, it is not necessary to concern about the instability due to the difference in weight between the main and inertia bodies but the assembling and parameter tuning would become more complicated. Fig. 2(d) shows a unique structure that utilizes the gravity acting on the inertia body, in which the inertia body is suspended by two SMA wires diagonally extended owing to the weight of the inertia body. This structure could perform bidirectional movement by controlling the activation of the two SMA wires. Finally, Fig. 2(e) illustrates a structure based on the SIDM