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Development of bi-stable and millimeter-scale displacement actuator using snap-through effect for reciprocating control fins

Choon-Gil Kang [a,b], Jun-Seong Lee [a], Jae-Hung Han [a,*]

[a] Dept. of Aerospace Eng., KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea
[b] Agency for Defense Development, 488 Bugyuseong-daero, Yuseong-gu, Daejeon 305-152, Republic of Korea

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ABSTRACT

A new two-step amplifying mechanism combining a lever-arm with flexure hinges and a pre-curved thin shell structure is proposed to make a millimeter-scale linear actuator. A large amplification ratio can be obtained by the snap-through effect of a post-buckled shell structure without losing actuation force. The snap-through phenomenon of pre-curved thin-plate are numerically analyzed by using the finite-element software ABAQUS to specify the trigger force and displacement required to initiate the snap-through. The analytic results are in good agreement with the test results for the pre-curved shell structure. The trigger force and displacement for snap-through are supplied by the lever-arm with the piezo stack actuator. Amplification ratio of the lever-arm is drastically changed according to the external load. The lever-arm mechanism is designed to have enough actuation force and displacement to satisfy requirements such as trigger force and displacement of the bi-stable structure. The components of the designed actuators are manufactured and integrated. The designed two-step amplified actuator is experimentally validated to operate with an 8 mm stroke and 2 Hz bandwidth.

1. Introduction

Reciprocating control fins have been newly proposed for conventional projectiles in order to stabilize and control orientation angles and rotational rates so that the eventual targeting accuracy can be improved in terms of the circular error probable (CEP) [13]. Typically the fins are placed mostly inside of the cylindrical body and suddenly pop out to produce additional control forces and moments. In other words, on-off control inputs repetitively activate or deactivate the control fins up until the projectile hits the target. Using similar Monte Carlo simulations as in [4], reciprocating control fins with the stroke amplitude of 8 mm show satisfying CEP correction performance even when they are operated very slowly (∼ a few Hz). A compact linear actuator that drives the conceptual fins with those amplitude and operating frequency requirements needs to be designed and fabricated.

Piezo-ceramic actuators have advantages including broad bandwidth of actuating frequency, high blocking force, and compact size, where piezoelectric materials directly transform the input of electrical power to mechanical displacement. However, the ranges of displacement are limited to micrometer scales; for example, commercial piezo stack actuators (e.g. P-842–P-845 PI products) travel only 15–90 μm [11]. In order to use piezo actuators in millimeter scales, a mechanical device that amplifies the changes of displacement needs to be designed and assembled with those piezoelectric actuators. Interfacing both the amplification mechanisms and the piezoelectric actuator might highly affect the overall amplified displacement and bandwidth of operating frequency: trade-off design should be repeated until the desired functional requirements, such as displacement, actuation force and frequency, have been satisfied.

By adjusting the location of the fulcrum, lever mechanisms have often been applied to magnify applied force. Once we have sufficiently high input force with short moment-arm from the pivot, output displacement of the other end of the lever with longer moment-arm can be amplified to counterbalance the applied moment at the fulcrum. To achieve the high amplification ratio with sufficient mechanical strength, various types of flexure hinge combined with lever or bridge have been proposed in the previous studies [6,8,18]; however, those actuators were reported to make only 1 mm maximum displacement due to losses found in the complex shapes and combinations of flexure hinges. The desired amplification ratio might be difficult to achieve by single amplification method; multiple amplifications with minimal deficiency need to be considered.

In the light of the post-buckled behavior of a shell structure, large changes in shape can also be obtained by snap-through effect without a continuous power supply [10,14]. For instance, pre-curved thin-plate with the fixed–fixed boundary condition has two stable curved shapes and the snap-through effect makes the plate deform between two equilibriums with the maximum change of

* Corresponding author.

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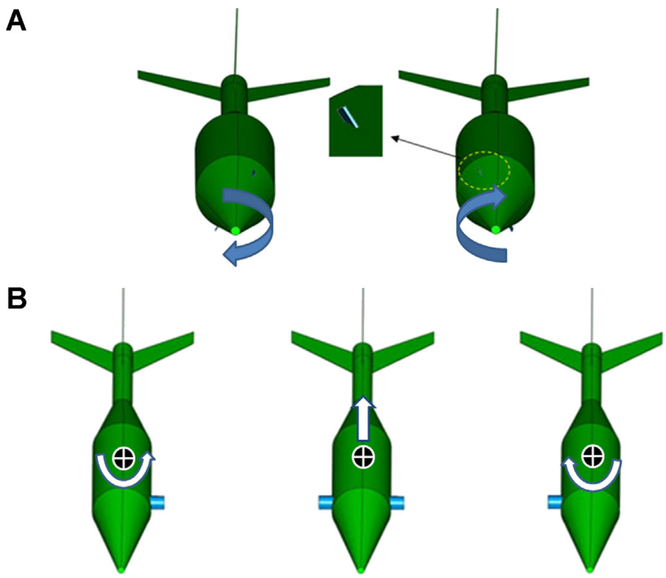

Fig. 1. Schematics of projectiles equipped with reciprocating control fins. (A) Configuration of roll rate control, and (B) configuration of yaw rate and range control.

displacement at the center of the plate. Transition between stable states can be controlled by smart actuators, such as macro-fiber composites and shape memory alloys, where the actuators drive the structure to have a unidirectional snap-through [1–3,12,14]. The required travel range of the reciprocating control fins can be efficiently realized by the snap-through effect of a structure if it is controlled in bi-directional ways.

In this study, a bi-stable and millimeter-scale displacement actuator using snap-through effect for reciprocating control fins is designed and fabricated to experimentally validate the actuator performance. The desired range of displacement is obtained by the two-step amplification of micrometer-scale displacement of a piezo stack actuator: using (1) a lever-arm with flexure hinges, and (2) the snap-through effect of thin-plate structure. The post-buckled characteristics of pre-curved thin-plate are numerically analyzed by using finite-element methods. A parametric study on the plate is also conducted to specify functional requirements such as trigger force and displacement, which should be produced by the lever-arm with flexure hinges and piezo stack actuator. By applying the rigid-body assumption on lever and hinge, the dimension of the lever-arm with flexure hinges is briefly determined. Much of its detailed design is made using finite-element analysis. The components of the designed actuator are separately manufactured and carefully integrated; the developed actuator shows the stroke of 8 mm and the operating frequency of 2 Hz in performance test.

2. Functional requirements of reciprocating control fin actuator and its components

Conventional projectiles have a limited accuracy: the flight path cannot be corrected once the projectile is launched. The addition of the reciprocating control fins to the projectile as shown in Fig. 1 allows us to control the projectile; various combinations of active (popped-up) fins stabilize roll rate or control yaw rate, to increase the precision of the projectile and simultaneously decelerate the projectile due to the addition of drag on the active fins. Note that the arrows indicate the control forces and moments resulting from various combinations of active control fins.

This paper proposes a reciprocating control fin actuator, as shown in Fig. 2, which consists of three components: (1) a piezo stack actuator, (2) a lever-arm with flexure hinges, and (3) a pre-curved thin-plate. For the piezo stack actuator, a commercially available product, P845-60, was particularly chosen whose push/pull force P_{PSA} is 3000 N/700 N [11]. The displacement of the piezo stack actuator d_{PSA} is reported to be 90 μm under the applied voltage of 100 V. Thus, approximately 90 times amplification of d_{PSA} is required to directly obtain the maximum stroke of the pre-curved thin-plate, $2d = 8$ mm, at its center location.

The pre-curved shape of the thin-plate with snap displacement d can be adjusted by the distance L_i between two fixed boundary points which is smaller than the length of thin-plate L. As L_i is decreased, the displacement amplification ratio of thin-plate d/d_t is increased, but much larger trigger force P is required. The trigger force and trigger displacement d_t at the interface point L_p are transferred from the lever-arm to the thin-plate via a snap-through trigger interface, as shown in Fig. 2. The trigger force and trigger displacement should be carefully determined to satisfy the capability of the integrated lever-arm with flexure hinges and the piezo stack actuator. The lever-arm with flexure hinges should provide the amplification ratio d_t/d_{PSA} with P at the end of the lever-arm.

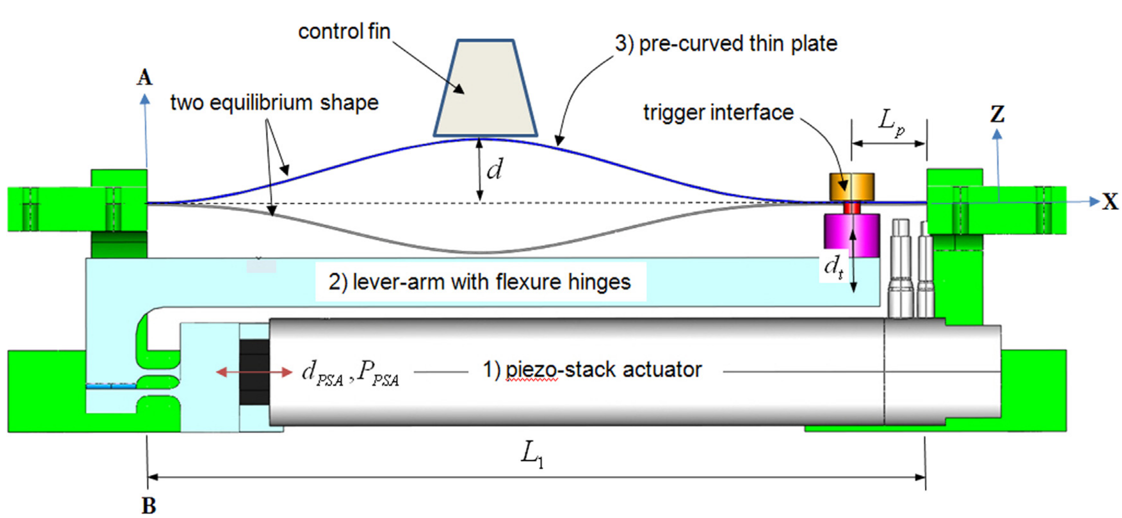

Fig. 2. Cross sectional drawing of the proposed bi-stable and millimeter scale displacement actuator.