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Research paper

Amplification ratio analysis of a bridge-type mechanical amplification mechanism based on a fully compliant model

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ABSTRACT

This study proposes a new mathematical model for the amplification ratio of a single-stair bridge-type amplification mechanism. To overcome the limitations of previous models, all members of the amplification mechanism are assumed to be compliant. The proposed model is compared to conventional models as well as analysis results using finite element models, after which the effects of the dimensions of each member are investigated. In addition, design optimization is carried out. Finally, the usefulness of this mathematical model is verified by an experiment using the optimally designed mechanism. As a result, the proposed mathematical model very aptly describes the displacement amplification ratio of the single-stair bridge-type amplification mechanism.

1. Introduction

Most piezo-driven stages embed flexure-based mechanical amplification mechanisms to magnify the displacement of piezo actuators. Because a stack-type piezo actuator can generate displacement of approximately 0.1% of the length of the piezo stack [1,2], the displacement is limited to several tens of microns. Therefore, applications with several tens to several hundreds of microns require mechanical amplification mechanisms.

There are two types of flexure-based mechanical amplification mechanisms which can be used to amplify the displacement of piezo actuators. The first of these is a lever-type amplification mechanism [3] and the second is a flextensional amplification mechanism [4]. In the flextensional amplification mechanism, force applied by a linear actuator between two input members induces bending and tension of flexural members in the mechanism. As a result, the displacement of an output member is magnified compared to that of the actuator. The direction of the output displacement is perpendicular to that of the input displacement. Flextensional amplification mechanisms can be categorized as Moonie actuators [5–7], Cymbal actuators [8,9] and bridge-type mechanisms [1,10–20]. In addition, the RAINBOW actuator [21,22] and THUNDER actuator [21] are similar to the flextensional amplification mechanism, with bendable piezo ceramics replacing the flexure members.

The structure of the lever-type amplification mechanism is so simple that the amplification ratio is intuitive. However, a higher amplification ratio requires a longer lever arm which causes a larger volume. Compared to this type, the bridge-type mechanical amplification mechanism has a compact structure. Given that the amplification ratio of the bridge-type mechanism is determined by the slope of the bridge in the mechanism, a higher amplification ratio can be accomplished

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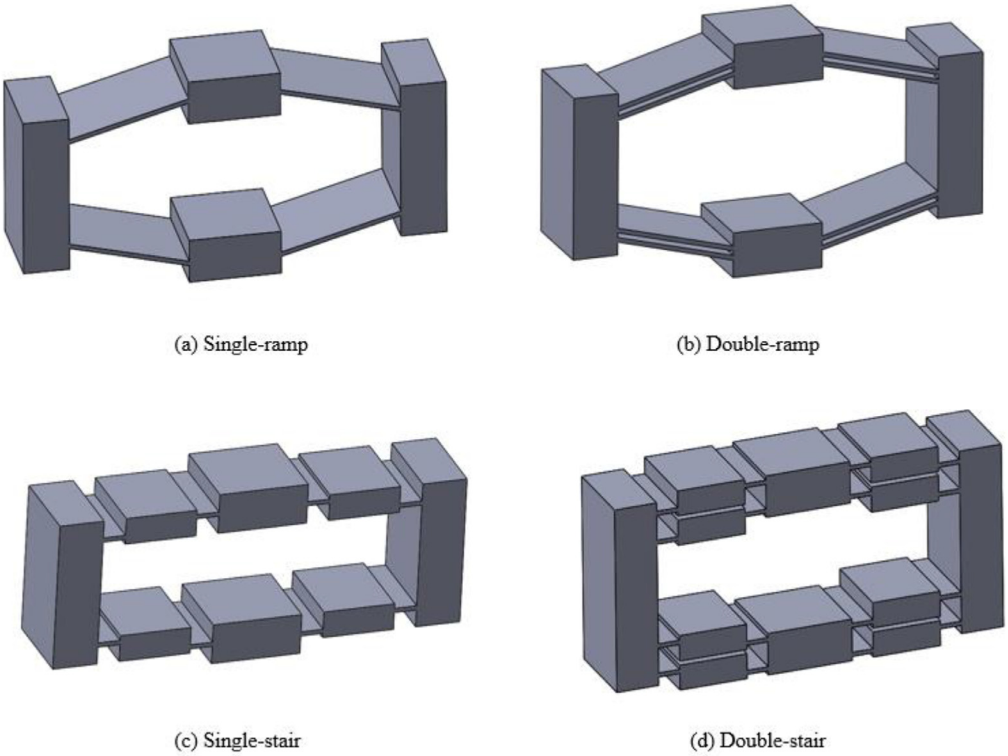
(a) Single-ramp (b) Double-ramp

(c) Single-stair (d) Double-stair

Fig. 1. Four types of bridge-type mechanical amplification mechanisms.

when using an identical volume for the mechanism. However, while amplification ratio of the bridge-type mechanism cannot be calculated intuitively, it can be expressed by a complex equation.

There exist various bridge-type amplification mechanisms. We can classify them as the single-ramp [1,10], double-ramp [20], single-stair [11–16] and double-stair [17,18] types according to the shape of the bridge, as shown in Fig. 1. In addition, double amplifying mechanisms [19,20] have been devised using nested single-stair bridge-type amplification mechanisms. Many researchers are interested in the amplification ratio of the bridge-type amplification mechanism, especially with the single-stair type, and they have employed them in fine-motion stages [14–16,23–25].

Several mathematical models have been developed to calculate the amplification ratio of the bridge-type amplification mechanism. [10–13,18,20] In the single-stair cases [11–13], the mathematical models assumed that only flexure hinges are deformed while the other members remain rigid. The amplification ratios calculated by the mathematical models can be expressed mainly by the slope of the bridge in the mechanisms, which increases abruptly and then decreases slowly with the slope angle. The amplification ratios calculated by these models are in accord with cases analyzed by the finite element models, except in the vicinity of the maximum value, in which the calculated amplification ratios show considerable errors compared to analysis results using finite element models. The errors stemmed from the assumption that only flexure hinges are deformed. Therefore, the development of a fully compliant model is required to overcome this problem.

In this study, an enhanced mathematical model for the single-stair bridge-type amplification mechanism is developed to estimate the amplification ratio of the mechanism. All mechanical members of the mechanism are assumed to be compliant. The proposed model is compared to previous models as well as analysis results using finite element models. The effects of the dimensions of each member are investigated. In addition, an optimal design is carried out. Finally, the usefulness of this mathematical model is verified by an experiment using the optimally designed mechanism.

2. Modeling of the bridge-type amplification mechanism

The flexure-based bridge-type amplification mechanism with a single-stair consists of 16 members forming a fixed body, two input bodies, one output body, four medium bodies and eight flexure hinges. In most cases, the input bodies are applied by pushing force, after which the output body moves downward. The flexures connect between the input body and the output body as well as the input body and the fixed body. The offset between the flexures attached to the ends of the medium body causes the motion of the output body.

A quarter of the mechanism, shown in Fig. 2, is considered in the analysis. The dimensions of the members are expressed by L, l, H, and h. The width h is half of the width H, and the length l is half of the length L. The subscripts of the dimensions