Mechanism and Machine Theory 99 (2016) 176–188

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

A new model analysis approach for bridge-type amplifiers supporting nano-stage design

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ARTICLE INFO

Article history:
Received 11 May 2015
Received in revised form 12 December 2015
Accepted 11 January 2016
Available online 30 January 2016

Keywords:
Bridge-type amplifier
Displacement amplification ratio
External load
Elastic beam theory
Guiding mechanism
Finite element analysis (FEA)

ABSTRACT

This paper presents a new analysis method for bridge-type amplifiers by incorporating the effect of external loads, and establishes a theoretical model to predict the input/output displacement amplification ratio based on elastic beam theory. The new analytical model indicates that the displacement amplification ratio of the bridge-type amplifiers decreases significantly in the presence of external loads, and its changing rate increases with higher external loads. The analysis method is then applied to the modeling and design of a bridge-type-amplifier based nano-manipulating stage, where the guiding mechanism acts as the external load of the bridge-type amplifiers. It is shown that the new analysis method can derive more accurate model of the nano-stage, which is further verified by the finite element analysis (FEA) results. The proposed method offers a new look into the analysis and design of flexure based nano-stages for real applications.

1. Introduction

With the rapid development of advanced manufacturing and measuring techniques, nano manipulating system has become one of the key enabling components in precision instruments [1,2,3]. To satisfy the ultrahigh precision requirement, the smart micro actuators (such as piezoelectric actuators) and various compliant mechanisms have been extensively researched due to their characteristics of high resolution, high bandwidth and fast response [4,5,6,7]. In particular, flexure hinges are key components in compliant mechanisms to generate motions through elastic deformation. Different from traditional revolute joints, the design and analysis of flexure hinges has general challenging issues, such as finite stiffness in the output direction and the drift of the rotational center [8], and has attracted significant research efforts, see e.g. Tian et al. [9,10] and the references therein.

Note that many practical applications such as biological cell manipulation and micro-fluidic chip technology [11,12] usually require a large motion range of more than hundreds micrometers, which is significantly larger than the output displacement of micro actuators. For example, the stroke of a PZT (piezoelectric actuator) is about 0.1% of its own length [13]. Therefore, various displacement amplification mechanisms have been developed supporting nano-manipulating systems, such as lever-type [14,15], bridge-type [13,16], four-bar linkage [17], and Scott-Russell mechanism [18]. In particular, the bridge-type amplifier has attracted significant research and various analytical models have been proposed to predict the amplification ratio, thanks to its compact structure and large displacement amplification ratio.

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http://dx.doi.org/10.1016/j.mechmachtheory.2016.01.005

According to the pseudo-rigid-body model, the flexure hinge can be simplified as an ideal revolute joint associated with a torsional spring and other elements can be taken as rigid bodies. Pokines [19] and Lobontiu [20] derived the ideal displacement amplification ratio of the bridge-type mechanism based on geometric relationship analysis respectively. Ma [13] further simplified the ideal model through instantaneous velocity analysis. Furthermore, considering the effect of translational deformations of the flexure hinges, Ma [13] derived a theoretic displacement amplification ratio using elastic beam theory. Qi [21] further analyzed the input and output displacements through both geometric relations and elastic beam theory and proposed a novel theoretical displacement amplification ratio formula accordingly. Moreover, by assuming flexure hinges as 6 degree-of-freedoms (DOFs) spring elements, Kim [22] proposed the matrix method to model a spatial two-step bridge-type amplifier. With the consideration of both the flexure hinges' and connecting arms' deformations, Xu [16] established the analytical model of a flexure-based compound bridge-type (CBT) displacement amplifier. However, most existing models only focused on the characteristics of the individual amplifier. In fact, we have observed that the actual amplification ratio of the bridge-type amplifier in nano-manipulating systems is different from that of the individual amplifiers because of the significant impact of external loads, which inevitably exist in nano-stage systems.

In this paper, we take the effect of external loads into account and propose a novel theoretical model for bridge-type amplifiers. Through this new method, a more accurate displacement amplification ratio can be achieved for real applications. Then the proposed model is applied to the modeling of a bridge-type-amplifier based nano-manipulating stage, where the guiding mechanism acts as the external load of the bridge-type amplifiers. Comparisons between the analytical results and FEA results demonstrate the effectiveness of the proposed analysis method.

In the rest of the paper, the mechanism description of the bridge-type-amplifier based nano-stage is described in Section 2. Analytical static modeling of the bridge-type amplifier is derived in Section 3, where the effect of external loads on the performance is analyzed. In Section 4, the characteristics of the guiding mechanism is analyzed and the static model of the nano-stage is established. Section 5 verifies the established models by FEA method. Finally, some concluding remarks are summarized in Section 6.

2. Mechanism description

The schematic diagram of the designed piezo driven nano-stage with a bridge-type amplifier is depicted in Fig. 1. In the proposed nano-stage, the central motion platform is connected to the fixed frame through four leaf springs, which constitutes the guiding mechanism. Due to the leaf springs' characteristics of high longitudinal stiffness, low transverse stiffness and low stress concentration, the guiding mechanism can well improve the nano-stage's rejection capability against parasitic motions and other external disturbances [23,24]. Therefore, the proposed nano-stage can move only in the desired direction due to the structural symmetry.

The piezo stack is adopted as the actuator for the nano-stage, thanks to its characteristics of high resolution, high force, high stiffness and fast response. It is located inside the bridge type displacement amplification mechanism, as shown in Fig. 2. The output end of the amplifier is connected to central motion platform. Therefore, the output of the piezo stack is amplified by the bridge-type mechanism and then transferred to the central motion platform accurately. Moreover, the corner-filleted flexure hinges are used in this displacement amplifier because they are more flexible than other types of flexure hinges of the same size. Obviously, in this particular design, the guiding mechanism acts as the external load of the bridge-type amplification mechanism.

As depicted in Fig. 1, the design also incorporates a preload mechanism consisting of four bolts and two compressed springs. With the requirements of assembly, adjustment and looseness-proof of the piezoelectric actuator, two bolts with fine threads are mounted behind the piezoelectric actuator to provide a certain preload. For the purpose of adjusting the preload of the piezoelectric actuator, two compressed springs are symmetrically mounted at the left and the right sides of the bridge-type amplifier by two bolts. The preload is thus applied by tightening the screws, which press the amplifier against the piezoelectric actuator and align the piezoelectric stack with the desired force. In addition, the compressed springs also improve the stiffness of the nano-stage with this arrangement. It is also noted from Fig. 1 that a linear encoder (by *MicroE Systems*) with a resolution of 1.2 nm is used as the displacement sensor to generate real time position signals on the motion direction.

3. Analytical modeling of bridge-type amplifier

In this section, we first recall several analytical models of the bridge-type amplification mechanism. These models can well predict the amplification ratio of the individual bridge-type amplifiers. However, in most nano-manipulating systems, the bridge-type amplifiers are usually connected to specific driving devices. The simulations and experimental results show that the amplification ratio of the bridge-type amplifiers in nano-manipulating systems is significantly different from the individual amplifiers due to the effect of external loads on amplifiers' performance. Therefore, a new analysis method for bridge-type amplifiers is developed in this section by incorporating the effect of external loads.

3.1. Previous analysis models of bridge-type mechanism

Fig. 2 shows the schematic of bridge-type mechanism. With the simplification that all the flexure hinges are considered as ideal pivots and other elements are taken as rigid bodies, the ideal multi-rigid body schematic of the bridge-type amplifier is shown in Fig. 3. Therefore, a pseudo-rigid-body model of the amplifier is constructed and various methods can be applied to analyze the bridge-type mechanism.