Design of a precision flexural linear stage system with sub-nanometer resolution and 12-mm travel range

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Abstract. Precision ball-bearing-based or roller-bearing-based positioning stage systems are capable of providing a large travel range. However, it is not possible to meet requirements in sub-nanometer positioning resolution, high tilting stiffness, and microradian-level straightness of trajectory repeatability with a simple rolling element guiding system. To meet those requirements and still allow for large travel range, we have designed a novel precision flexural linear stage. It is capable of sub-nanometer positioning resolution and 12-mm travel range for synchrotron radiation instrumentation applications. The design and preliminary test results for a prototype stage system are discussed in this paper.

1. Introduction

Recently, there are more synchrotron radiation instrument applications that require a very high reproducibility for multidimensional linear positioning systems with nanometer or sub-nanometer resolution. In the travel range of less than a few hundred microns, commercial PZT-driven flexural linear stages are available. Commercial-precision ball-bearing-based or roller-bearing-based linear positioning stages are capable of providing a much larger travel range. However, their positioning resolution is limited by the friction of the bearing-based guiding system. Moreover, their linear motion straightness of trajectory usually is not repeatable due to the roundness errors of the bearing’s rolling element and the uncertainty of the rolling ball’s or roller’s sliding effect.

Linear flexural stages (APS T8-31 and T8-32), with 3-mm travel range using fishbone-shaped multiple parallelogram weak-link structures, have been developed at the Advanced Photon Source (APS) at Argonne National Laboratory (ANL) \cite{1}. To further extend the travel range of the linear flexural stage and keep the stage compact, a prototype of a new T8-52 flexural linear stage system was designed and constructed at the APS using novel deformation-compensated flexural pivot mechanisms \cite{2}. Design of the precision flexural linear stage system and its preliminary test results are discussed in this paper.

2. Design of the T8-52 flexural linear stage

The initial design goal for the T8-52 flexural linear stage is to develop a flexural nanopositioning horizontal linear stage with a travel range of 6-12 mm, load capacity of 1-2 kg, and dimensions within 150 (L) x 75 (W) x 33 (H) mm. The stage’s travel range and load capacity will vary for the different types of flexural pivots that are installed.
2.1. The basic deformation compensated linear guiding mechanism

The novelty of this new stage design is its deformation-compensated flexural-pivots-based linear guiding mechanism. The traditional parallel mechanism can provide a precise linear motion if the rotations on the pivots are perfect. However, the rotations with flexural pivots are always associated with center shift dynamic errors [3-5]. To fully compensate these errors, a basic parallel mechanism with evenly distributed flexural pivots has been designed. As shown in figure 1, the basic parallel mechanism includes seven elements linked by eight commercial flexural pivots: two parallel bars; four I-link bars; and one U-shaped middle bar. The center shift dynamic errors of each flexural pivot are measured or analyzed before the assembly process. The precision linear motion is approached with the fine tuning, pairing, and optimizing of the orientation of each flexural pivot.

![Figure 1. Left: A 3D model of the deformation-compensated flexural-pivots-based linear guiding mechanism. Right: A 3D model shows a FEA study with near 6-mm displacement.](image)

2.2 The T8-52 stage linear guiding system

As shown in figure 2, three sets of deformation-compensated flexural linear guiding mechanisms are applied on the stage. Two sets of the linear guiding mechanisms are mounted vertically between the stage base and carriage to provide the stage vertical load capacity. One set of the linear guiding mechanism links the stage base and carriage horizontally to enhance the stage linear guiding and provide lateral stiffness. There are synchronizing linkages between the U-shaped middle bars of the three sets of guiding mechanisms to integrate the three sets of guiding mechanisms into a one-stage guiding system. Figure 3 shows the 3D models for stress and displacement simulations using the finite element analysis method.

![Figure 2. 3D models of the prototype of T8-52 flexural linear stage system.](image)

2.3. The combined drivers

The prototype of the T8-52 stage is driven by the combination of a commercial PZA-12 PZT motor from Newport™ mounted on the stage base and a commercial P-841.10 PZT actuator from PI™ mounted on the stage carriage. The PZT motor provides 12-mm travel range with 100-nm resolution, and the PZT actuator drives the stage with sub-nanometer positioning resolution in a 15-micron travel range. A set of compression springs provides the preloading force between the PZT motor and the PZT actuator to minimize the motion backlash.
2.4. The optical encoder for closed-loop positioning control

As shown in figure 2, a 3500 Si grating optical encoder with 5-nm resolution from MicroE Systems™ measures the stage carriage position related to the stage base. To control the stage with 10-nm closed-loop resolution in a 12-mm travel range, a coarse-to-fine strategy is realized by motion relay between the PZT motor and the PZT actuator.

In applications with nanometer- or sub-nanometer-level positioning, a laser interferometer with sub-nanometer resolution will be used for the closed-loop positioning control.

3. Preliminary test

We started the preliminary test for the prototype T8-52 stage with two sets of laser interferometer systems. Figure 4 shows a photograph of the stage prototype and the test setup with laser interferometers. The left side of figure 5 shows the stage linear motion straightness of trajectory in the pitch direction. The right side of figure 5 right shows 5-nm steps performed by the stage with open-loop control.

4. Discussion

A prototype of the new flexural linear stage system T8-52 was designed and constructed at the APS using novel deformation-compensated flexural pivot mechanisms. Preliminary tests for the stage
performance have started. More stage motion tests with grating optical encoder and laser interferometer closed-loop controls are forthcoming.

Based on this new mechanical design, similar stages will be built for synchrotron radiation instrumentation applications, such as ultra-precision linear positioning stages for x-ray nanoprobes and linear stages for x-ray optics switching.

Figure 5. Left: A diagram of the stage linear motion straightness of trajectory in the pitch direction. The synchronizing linkage between the vertical and horizontal guiding mechanisms is not installed and the guiding mechanisms are not fine-tuned during the test. Right: A diagram shows three 5-nm steps performed by the prototype T8-52 stage with open-loop control.

5. References
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