MECHANICAL DESIGN OF COMPACT VERTICAL AND HORIZONTAL LINEAR NANOPOSITIONING FLEXURE STAGES WITH CENTIMETER-LEVEL TRAVEL RANGE FOR X-RAY BEAMLINE INSTRUMENTATION

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Abstract

Nanopositioning techniques present an important capability to support the state-of-the-art synchrotron radiation instrumentation research for the Advanced Photon Source (APS) operations and upgrade project. To overcome the performance limitations of precision ball-bearing-based or roller-bearing-based linear stage systems, compact vertical and horizontal linear nanopositioning flexure stages have been designed and developed at the APS with centimeter-level travel range and nanometer-level resolution for x-ray beamline instrumentation applications. The mechanical design and finite element analyses of the APS T8-55 and T8-56 flexural stages, as well as its initial mechanical test results with laser interferometer are described in this paper.

INTRODUCTION

Commercial-precision ball-bearing-based or roller-bearing-based linear positioning stages are capable of providing larger travel range with compact sizes. However, their linear motion straightness of trajectory is usually 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. For many synchrotron radiation instrument applications, compact flexure stages with repeatable and stable nanopositioning performance will simplify the control mechanism for the design of multi-dimensional scanning or alignment apparatus. Using commercial flexural pivots, several design enhancements were developed at the APS to make the traditional parallel mechanism more precise and compact.

Flexural-Pivots-Based Deformation Compensated Linear Guiding Mechanism

The deformation-compensated flexural-pivots-based linear guiding mechanism was developed at the APS in 2011 [1,2]. Figure 1 (Left) shows the basic parallel mechanism of the APS T8-52 prototype horizontal stage. It includes seven elements linked by eight commercial flexural pivots: two parallel bars; four I-link bars; and one U-shaped middle bar. The center-shifting 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 [3].

Middle-Bar Relative Position Control Mechanism

To enhance the stiffness of the parallel flexure linear guiding mechanism, a new middle-bar relative position control mechanism was developed at the APS. Figure 1 (Right) shows a top-view and a side-view of the middle-Bar relative position control mechanism integrated with the APS T8-54A prototype horizontal stage's linear guiding mechanism [4-6].

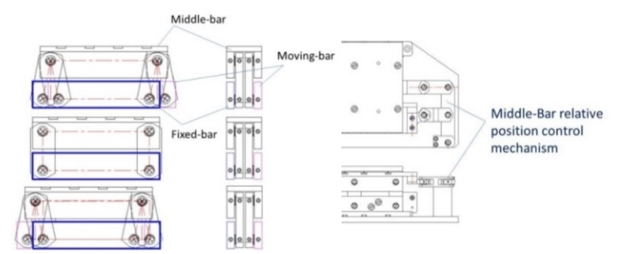

Figure 1: Left: Schematic of the basic parallel mechanism for the flexural-pivots-based linear flexure stage. Right: Schematic of the top-view and a side-view of the middle-bar relative position control mechanism.

T8-55 VERTICAL FLEXURE STAGE

The design of the APS T8-55 vertical flexure stage is based on the requirement of a sample scanning stage for x-ray microscope with 4 kg vertical load. The initial design goal for the T8-55 flexural linear stage is to develop a flexural nanopositioning vertical linear stage with a travel range of 12 - 16 mm, load capacity of 2 - 4 kg, and dimensions within 146 (L) x 185 (W) x 160 (H) mm. The stage's travel range and load capacity will vary for the different types of flexural pivots that are installed.

As shown in Figure 2, the T8-55 stage consists of a stage base, a symmetrically configured flexure linear guiding mechanism with precision motion enhancement structures, a decoupled linear driving mechanism driven by a micro-step stepper motor with harmonic gearhead, and a stage carriage [7].

The vertical flexure linear guiding mechanism has a symmetric structure with four vertical guiding panels. Each guiding panel includes two sets of the deformation-compensated flexural-pivots-based linear guiding mechanism which are mounted vertically between the stage base and carriage to provide a precision frictionless vertical motion guiding. A total of eight sets of flexural guiding mechanisms are applied on the stage. Figure 3 shows a 3D model for stress and displacement simulation of a single set of flexural-pivots-based linear guiding mechanism with near 6-mm displacement using the finite element analysis (FEA) method.

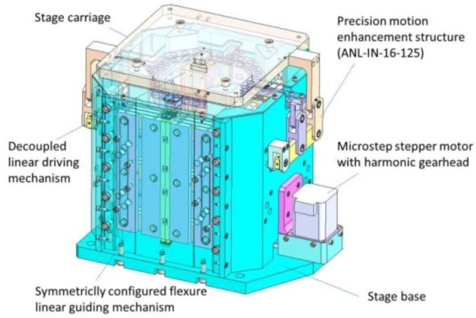

Figure 2: A 3-D model of the APS T8-55 vertical linear nanopositioning flexure stage with symmetric flexural-pivots-based precision linear motion guiding structure and precision motion enhancement structures.

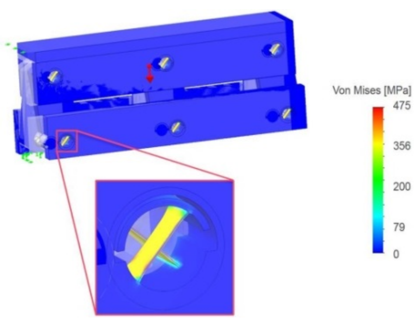

Figure 3: A 3D model shows a FEA study of a single set of flexural-pivots-based linear guiding mechanism with near 6-mm displacement.

To implement the precision motion enhancement [5] for this symmetric linear guiding structure, special weak-link mechanisms are applied to the middle-bar motion synchronizing linkage to compensate the transversal relative motions between the middle-bars as shown in Figure 4. The synchronizing linkages between the U-shaped middle bars of the guiding mechanisms integrate the eight sets of guiding mechanisms into a united stage guiding system.

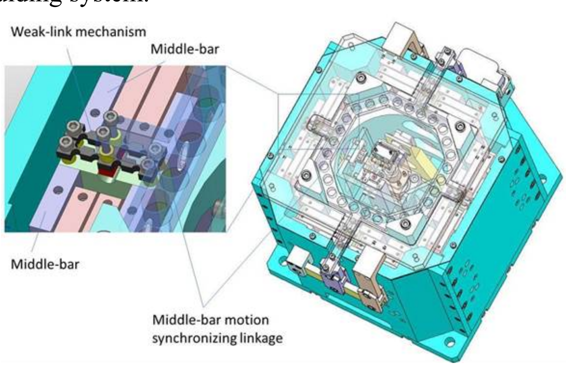

Figure 4: A 3-D model of the special weak-link mechanism applied to the middle-bar motion synchronizing linkage to compensate the transversal relative motions between the middle-bars.

T8-56 HORIZONTAL FLEXURE STAGE

The APS T8-56 linear flexure stage is designed for a horizontal sample scanning stage for x-ray microscope with a travel range of 12 - 16 mm, load capacity of 1 - 2 kg, and dimensions within 125 (L) x 347 (W) x 52 (H) mm. The stage's travel range and load capacity will vary for the different types of flexural pivots that are installed. Figure 5 shows a 3-D model of the APS T8-56 linear flexure stage.

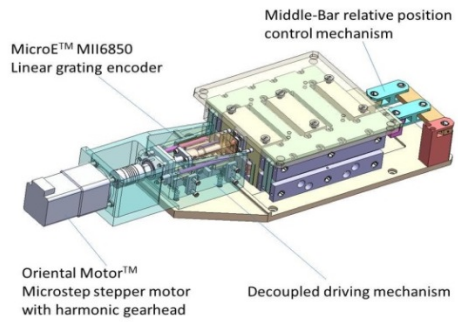

Figure 5: A 3-D model of the APS T8-56 horizontal linear nanopositioning flexure stage.

Similar to the APS T8-54A prototype horizontal stage's linear guiding mechanism, the T8-56 stage has three sets of deformation-compensated flexural linear guiding mechanisms. Two sets of the linear guiding mechanisms are mounted vertically between the stage base and carriage. One set of the linear guiding mechanism links the stage base and carriage horizontally. Synchronizing linkages between the U-shaped middle bars of the three sets of guiding mechanisms integrate the three sets of guiding mechanisms into a united guiding system.

COMBINATION OF THE T8-55 AND T8-56 FLEXURE STAGES

As shown in Figure 6, the sample scanning stage for the x-ray microscope at the APS Sector 2 is a combination of the APS T8-55 and T8-56 flexure stages. Table 1 and Table 2 summarize the design specifications of the APS T8-55 vertical linear flexural stage for the x-ray microscope sample 2D scanning stage application.

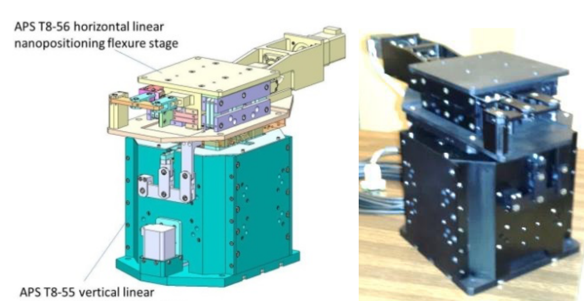

Figure 6: Left: A 3-D model of the combination of the APS T8-55 and T8-56 linear nanopositioning flexure stages for a 2D sample scanning stage system for x-ray microscope. Right: Photograph of the T8-55 and T8-56 vertical and horizontal linear flexural stage system.

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Table 1: Design Specifications of the APS T8-55 Vertical Linear Flexural Stage System

Max. load capacity	4 kg
Overall dimension	146 (L) x 185 (W) x 160 (H) mm
Stage weight	5.2 kg
Driving system	Oriental Motor™ stepper motor w/harmonic gearhead and timing belt
Linear encoder	MicroE™ MII 6850
Encoder resolution	10 nm
Stage travel range	16 mm
Min. incremental motion	2 nm
Max. driving speed	0.5 mm/sec

Table 2: Design Specifications of the APS T8-56 Horizontal Linear Flexural Stage System

Max. load capacity	2 kg
Overall dimension	125 (L) x 347 (W) x 52 (H) mm
Stage weight	1.9 kg
Driving system	Oriental Motor™ stepper motor w/harmonic gearhead
Linear encoder	MicroE™ MII 6850
Encoder resolution	10 nm
Stage travel range	16 mm
Min. incremental motion	2 nm
Max. driving speed	1 mm/sec

PRELIMINARY TEST RESULTS

The preliminary test for the APS T8-55 and T8-56 vertical and horizontal linear flexural stages is performed with an Attocube™ FPS3010 fiber-based three-axis laser interferometer system. Figure 7 shows the test setup for the T8-55 and T8-56 stages with laser interferometers mounted on an Invar reference frame at the APS nanopositioning support laboratory.

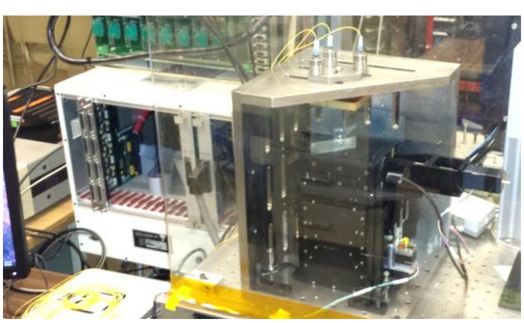

Figure 7: Photograph of the test setup for the T8-55 and T8-56 stages with laser interferometers mounted on an Invar reference frame.

As expected, the flexure linear guiding mechanism has a nanometer-level positioning capability. The flexure stage's positioning sensitivity is limited by its driving mechanism. Figure 8 shows a test of the T8-55 vertical flexure stage positioning sensitivity with five ~2.5 nm steps under a microstep stepper motor open-loop control. Figure 9 shows a ~ 0.5 mm/sec driving speed performed by the T8-55 vertical flexure stage driven by micro-steps (2 nm/microstep) under a pulse rate of 250k pulse/sec. All of the above tests for the T8-55 vertical flexure stage were performed under a 4 kg vertical load.

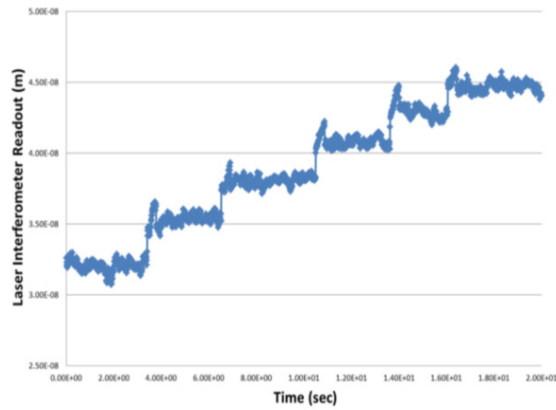

Figure 8: Test for the T8-55 vertical flexure stage positioning sensitivity with five ~2.5 nm steps under a microstep stepper motor open-loop control.

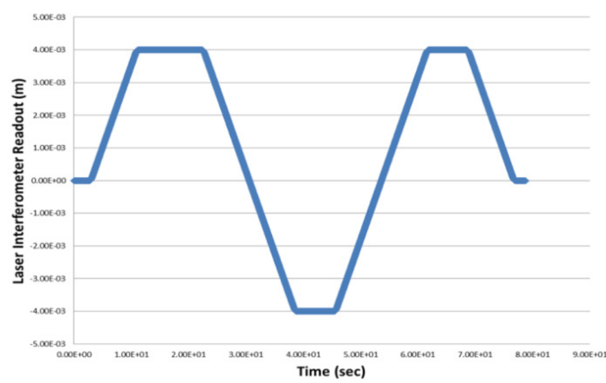

Figure 9: A ~ 0.5 mm/sec driving speed test of the T8-55 vertical flexure stage driven by micro-steps (2-nm/microstep) under a pulse rate of 250k pulse/sec.

SUMMARY

The mechanical design and finite element analysis of the APS T8-55 and T8-56 vertical and horizontal linear flexural stages, as well as preliminary mechanical test results are presented in this paper. Comprehensive mechanical tests for the APS T8-55 and T8-56 flexural stages with laser interferometer system are in progress.

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REFERENCES

[1] U.S. Patent granted No. 8,957,567, D. Shu, S. Kearney, and C. Preissner, 2015.
[2] D. Shu *et al.*, J. Phys. Conf. Ser. 425 212011(2013).
[3] W. Liu and G. Ice, "X-ray Laue Diffraction Microscopy in 3D at the Advanced Photon Source," in Strain and Dislocation Gradients from Diffraction, Imperial College Press, 2014, pp. 53-81.
[4] W. Liu *et al.*, AIP Conf. Proc. 1365, 108 (2011).
[5] D. Shu, W. Liu, S. Kearney, J. Anton, and J. Z. Tischler, Proceedings of SPIE-2015, Optomechanical Engineering conference, 9573-28, San Diego, CA, Aug. 2015.
[6] D. Shu, W. Liu, S. Kearney, J. Anton, B. Lai, J. Maser, C. Roehrig, and J. Z. Tischler, U.S. Patent application in progress for ANL-IN-16-125, 2016.
[7] D. Shu, B. Lai, S. Kearney, J. Anton, W. Liu, J. Maser, C. Roehrig, and J. Z. Tischler, U.S. Patent application in progress for ANL-IN-16-150, 2016.

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