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MECHANICAL DESIGN AND DEVELOPMENT OF COMPACT LINEAR NANOPOSITIONING FLEXURE STAGES WITH CENTIMETER-LEVEL TRAVEL RANGE AND NANOMETER-LEVEL RESOLUTION

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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, two compact linear nanopositiioning flexure stages have been designed and developed at the APS with centimeter-level travel range and nanometer-level resolution for x-ray experimental applications. The APS T8-54 linear flexure stage is designed to perform a precision wire scan as a differential aperture for the 3-D diffraction microscope at the APS sector 34, and the APS T8-56 linear flexure stage is designed for a horizontal sample scanning stage for a hard x-ray microscope at the APS sector 2. Both linear flexure stages are using a similar improved deformation compensated linear guiding mechanism which was developed initially at the APS for the T8-52 flexural linear stage [1,2]. The mechanical design and finite element analyses of the APS T8-54 and T8-56 flexural stages, as well as its initial mechanical test results with laser interferometer are described in this paper.

INTRODUCTION

X-ray Laue Diffraction 3D Microscopy developed at 34-ID beamline in the APS has been a unique and powerful tool for spatially-resolved structural studies at submicron level for materials science [3]. A precision linear stage is needed to perform a wire scan as a differential aperture for the 3-D diffraction microscope [4]. The wire scan motion is usually localized in a very short specific travel range after an initial large travel range alignment. Localized wear of the linear bearing stage, which causes an unrepeatable defect in the linear motion straightness of trajectory is always an issue for the results of the 3-D x-ray diffraction microscope.

To improve the linear motion performance and durability of the wire scan stage, a compact flexural-pivot-based precision linear stage APS T8-54 has been designed and constructed at the APS to replace the existing bearing-based linear stage for wire scan using deformation-compensated flexural pivot mechanisms as shown in Figures 1-3 [5]. Based on the experiences gained from the initial operation of the T8-54 flexure stage at the APS sector 34, a few design enhancements have been made to further improve the performance of the T8-54 stage. These design enhancements have also been implemented in the new compact flexure stage design for scanning sample stages at the APS sector 2. In this paper, we present the design enhancements for the T8-54 linear flexure stage, as well as the design of the new compact linear flexure scanning stage T8-56 for APS sector 2. Preliminary tests for the enhanced flexure linear guiding mechanism with laser confocal displacement meter and laser interferometer are also presented.

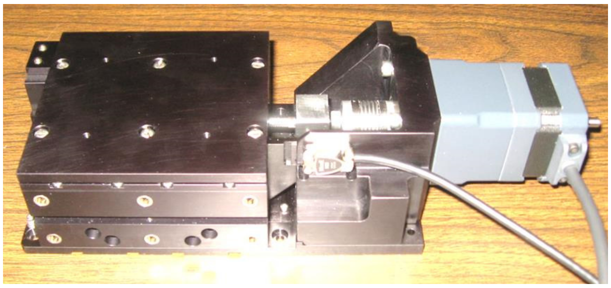

Figure 1: Photograph of the original APS T8-54 linear flexure stage for wire scan as a differential aperture for the 3-D diffraction microscope at the APS sector 34.

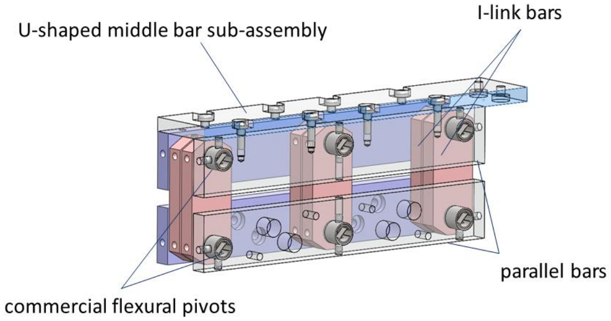

Figure 2: A 3-D model of the basic deformation compensated linear guiding mechanism for T8-54 linear flexural stage.

Figure 3: Photograph of the basic deformation compensated linear guiding mechanism for T8-54 linear flexural stage. A total of 12 C-Flex^{TM} D-20 flexural pivots are applied in the linear guiding mechanism.

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DESIGN ENHANCEMENT FOR T8-54A

As shown in Figure 4, two major design enhancements have been made for the updated compact linear flexure stage T8-54A:

- A new decoupled driving mechanism with MicroE™ MII6850 encoder replaced the original direct driving mechanism with MicroE™ M3500si encoder to reduce the stage's straightness of trajectory error caused by the ball screw direct driving mechanism and the grating encoder interpreter's error.
- A new middle-Bar relative position control mechanism [6] has been added to the stage's structure to enhance the stiffness of the flexure linear guiding mechanism.

Figure 5 shows a top-view and a side-view of the middle-Bar relative position control mechanism integrated with the T8-54A stage's linear guiding mechanism.

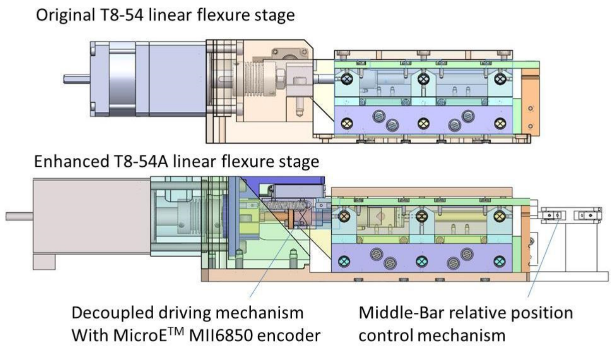

Figure 4: Side views of the 3-D models to compare the original T8-54 linear flexure stage and the enhanced T8-54A stage.

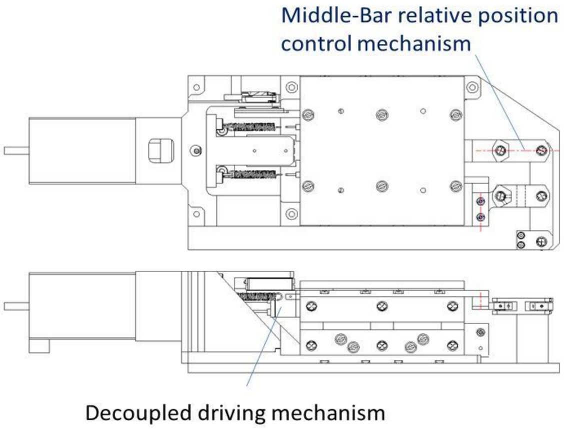

Figure 5: Top-view and side-view of the middle-Bar relative position control mechanism integrated with the T8-54A stage's linear guiding mechanism.

PRELIMINARY ANALYSES AND PROOF-OF-PRINCIPLE TEST FOR THE T8-54A DESIGN ENHANCEMENT

Preliminary finite element analysis (FEA) started with a single flexure linear guiding mechanism to simulate the effectiveness of the middle-Bar relative position control mechanism. A proof-of-principle experiment has also demonstrated a promising result with reasonable agreement with the FEA results. Figure 6 shows a 3-D model for the analysis of displacement of a single flexure linear guiding mechanism with control of the middle-bar relative position. Figure 7 shows a detailed view of the mesh distribution for FEA.

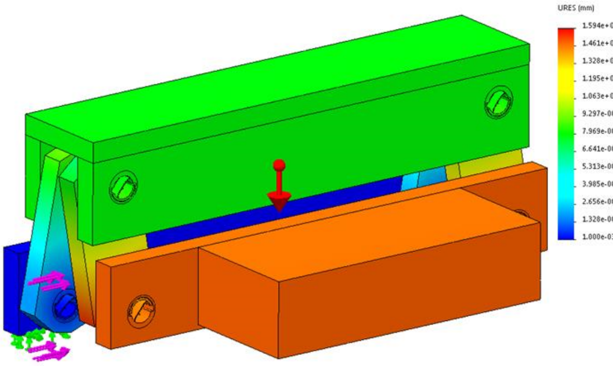

Figure 6: A 3-D model for the analysis of displacement of a single flexure linear guiding mechanism with control of the middle-bar relative position.

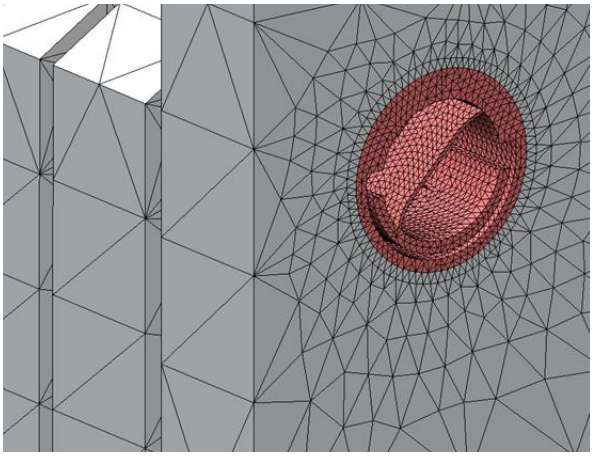

Figure 7: A detailed view of the mesh distribution for FEA 3-D model.

Preliminary test is also started with a single T8-54A flexure linear guiding mechanism with the middle-Bar relative position control. As shown in Figure 8, the relative horizontal positions of the carriage and the middle-bar of the guiding mechanism are positioned by two digital micrometers. A Keyence™ LT-9501 laser confocal displacement meter is used to measure the stage's parasitical vertical displacement. Figure 9 shows the differences between the conditions with a free middle-bar and a middle-bar with relative position control. The results showed that the stage's parasitical vertical motion is reduced to the level of ~1 micron rms over the 8 mm horizontal travel range while the middle-bar's relative horizontal position is controlled at a theoretical 1:2 position with carriage.

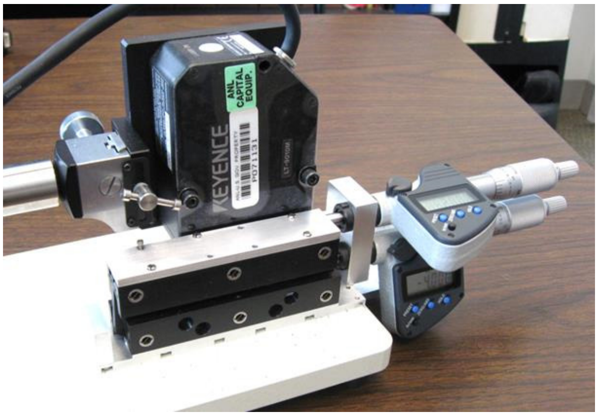

Figure 8: Photograph of the test setup with a single T8-54A flexure linear guiding mechanism with the carriage and middle-Bar relative positions controlled by two digital micrometers. A Keyence^{TM} LT-9501 laser confocal displacement meter is used to measure the stage's parasitical vertical displacement.

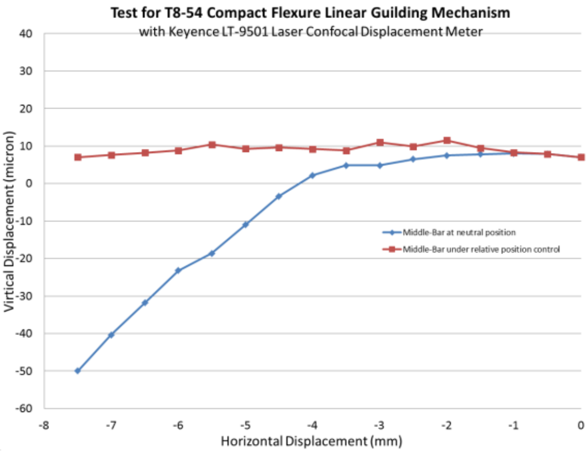

Figure 9: Preliminary test results showed the differences between the conditions with a free middle-bar and a middle-bar with relative position control.

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. We have tested the decoupled driving mechanism with 20 nm steps with Attocube^{TM} FPS3010 laser interferometer as shown in Figure 10. Figure 11 is a photograph of the updated compact linear flexure stage T8-54A.

DESIGN OF T8-56 COMPACT LINEAR HORIZONTAL FLEXURE STAGE

The APS T8-56 linear flexure stage is designed for a horizontal sample scanning stage for a hard x-ray microscope at the APS sector 2. The design enhancements for T8-54A have been implemented in this new compact flexure stages design. Figure 12 shows a 3-D model of the APS T8-56 linear flexure stage.

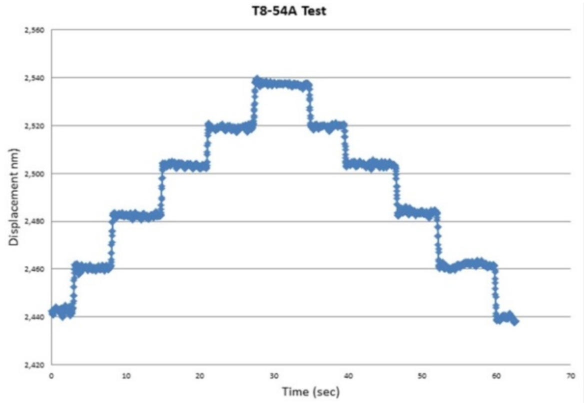

Figure 10: Preliminary test results showed 5-up and 5-down 20 nm steps performed by the decoupled driving mechanism with T8-54 flexure stage.

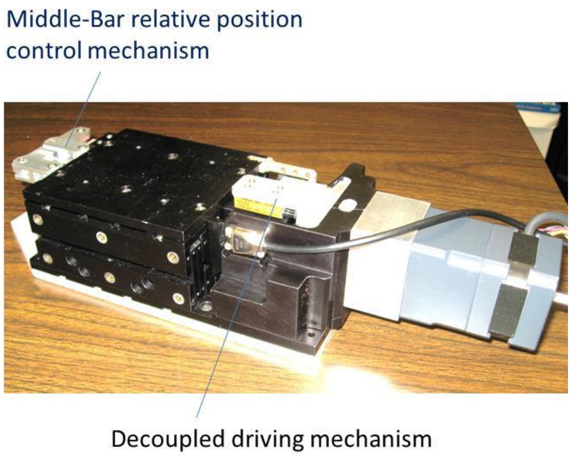

Figure 11: Photograph of the updated compact linear flexure stage T8-54A. The MicroE^{TM} M3500si grating encoder will be replaced by MII6850 grating encoder with reduced interpreter errors.

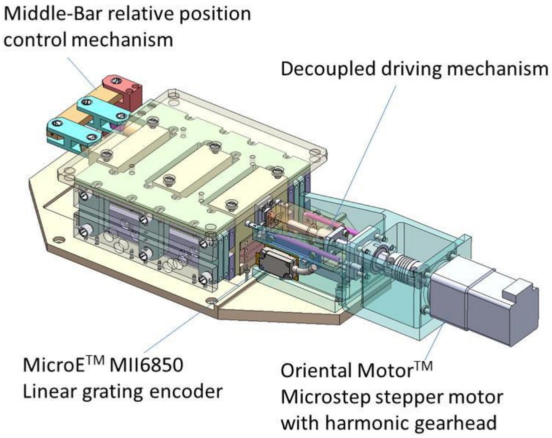

Figure 12: A 3-D model of the APS T8-56 linear flexure stage.

SUMMARY

The mechanical design and finite element analysis of the updated APS T8-54 and T8-56 flexural stages, as well as preliminary mechanical test results are presented in this paper. Comprehensive mechanical tests for T8-54A with laser interferometer system are in progress.

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