

Finite Element Study of Thermal Stability of the Multiple Fresnel Zone Plates Precision Alignment Apparatus for Hard X-ray Focusing

Jie Liu^a, Steven Kearney^{a,b}, Deming Shu^a

^aAdvanced Photon Source, Argonne National Laboratory
9700 S. Cass Avenue, Argonne, IL 60439, USA
jieliu@aps.anl.gov; shu@aps.anl.gov
skearney@aps.anl.gov

^bDepartment of Mechanical and Industrial Engineering, University of Illinois at Chicago
842 W. Taylor Street MC 251, Chicago, IL 60607, USA

Abstract - Fresnel-zone-plate based optics are broadly used on beamlines at the Advanced Photon Source (APS) at Argonne National Laboratory (ANL). The efficiency of Fresnel zone plates (FZPs) as focusing optics for hard X-rays depends on the aspect ratio of the zone height to the zone width. To achieve focusing spots in a few tens of nanometers, it is required to have very high aspect ratio, which is limited by current available fabrication techniques. One viable solution to this problem is to stack multiple zone plates in the intermediate-field to increase the effective zone plate height (Vila-Comamala et al., 2012). A mechanical design of multiple FZP precision alignment apparatus for hard X-ray focusing in 20 nm scale is proposed to align 2 to 6 zone plates simultaneously (Shu et al., 2014). One major challenge for the application of this apparatus is to compensate for the thermal shift and to maintain the thermal stability during beam time. This paper presents FE studies of the thermal displacement of the apparatus under different running conditions. The results are used to assist in determination of design parameters, selection of materials, and guiding the operation. Test results are also provided to validate the analysis results.

Keywords: Fresnel zone plate, multiple zone plate stacking, finite element study, thermal stability, hard X-ray focusing

1. Introduction

Fresnel-zone-plate (FZP) based optics are widely implemented for hard X-ray focusing on beamlines at Advanced Photon Source (APS) at Argonne National Laboratory (ANL). Moreover, the APS Upgrade project is planning to include hard X-ray nanoprobe beamlines that will require high efficiency with focusing spot in a few tens of nanometers [Web-1]. However, the efficiency of FZPs for hard X-ray focusing depends on the aspect ratio of the zone height over zone width. Due to limitations in the available fabrication methods, the aspect ratio of zone plate can only reach up to 20, which has limited the efficiencies of zone plates to be typically below 10% (Gleber et al., 2014). Increasing the aspect ratio and thereby increasing the diffraction efficiency of zone plates is a key to its application in the future. One method to effectively increase the aspect ratio is to stack multiple FZPs together. Vila-Comamala et al. had proven in their simulation that stacking of FZPs in an intermediate-field could substantially improve the diffraction efficiencies for hard X-ray focusing (Vila-Comamala et al., 2012). Based on this concept, several apparatuses for stacking 2, 3, and 6 FZPs were designed and fabricated by Shu et al (2014a, b).

Besides providing motions to allow precision alignment of FZP zone plates, these apparatus need to be carefully designed to minimize the thermal shift due to environmental temperature variations and to maximize the thermal stability over time. To achieve low thermal shift and high thermal stability, material and dimensions of the components need be carefully analyzed and selected.

2. Finite Element thermal and structural analysis

Material coefficients of thermal expansion (CTE) are, at best, on the order of $\mu\text{m}/^\circ\text{C}$; a 10^3 order higher displacement than the required nanometer level spot size. As a consequence, environmental temperature variations and internal heat load from the motors cause FZPs to misalign during operation. Therefore, to achieve such extreme thermal stability it is necessary to effectively cancel out thermal expansion by using multiple material types and/or changes in geometry. To study how the system would respond to these working conditions and assist in optimizing design, coupled finite element thermal and structural analysis studies were conducted. For all the designs, part or all of the following steps were carried out:

- 1) System response to environmental temperature change;
- 2) System response due to motor induced heat load;
- 3) Transient analysis to study the time response of the system to motor imposed heat load.

2. 1 Thermal analysis of Z2-33

Fig. 1 shows the 3D model of and mesh of Z2-33, a two zone plate stacking apparatus. Except stages, all major components were made of Al6061.

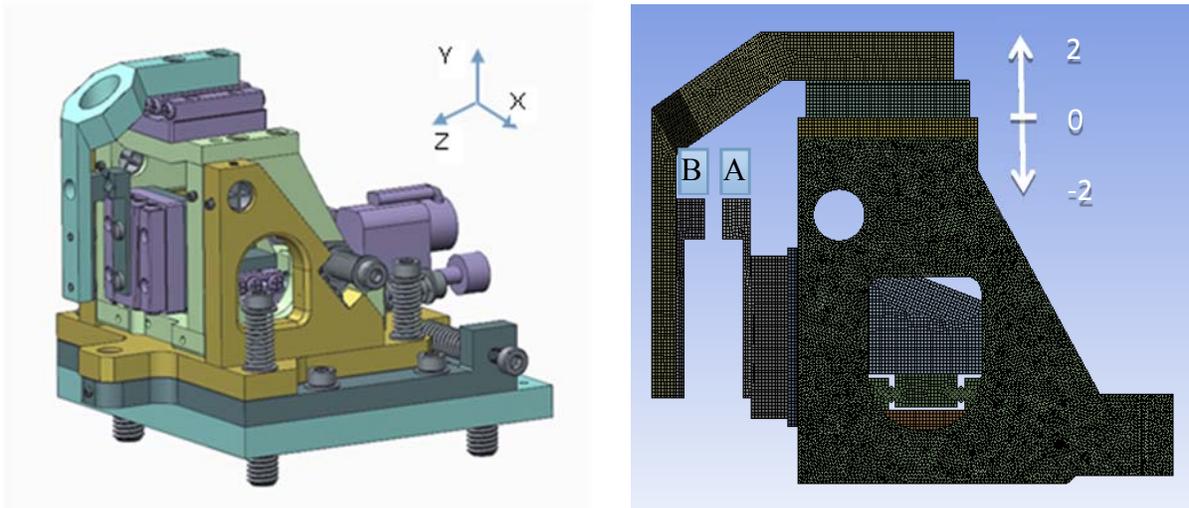


Fig. 1 Z2-33 CAD and FEA models

Temperature variation in the surrounding environment will cause the FZPs to shift relative to each other. The relative shift due to temperature variation is different for different holder locations. The relative FZP shifts in Y direction due to 1°C temperature rise when holder A is at different location in Y direction are shown in Fig. 2a for holder A made of both 1018 steel and 304 SS. The relationship between Y offset of holder A and the relative FZP shift is close to linear. The relative FZP shift is also affected by the CTE of the holder A material. Fig. 2b summarizes the relationship between the CTE of holder A

material to the relative FZP shift. From Fig. 2b, it can be seen that the relative FPZ shift in Y direction is almost linearly related with CTE of the holder A material.

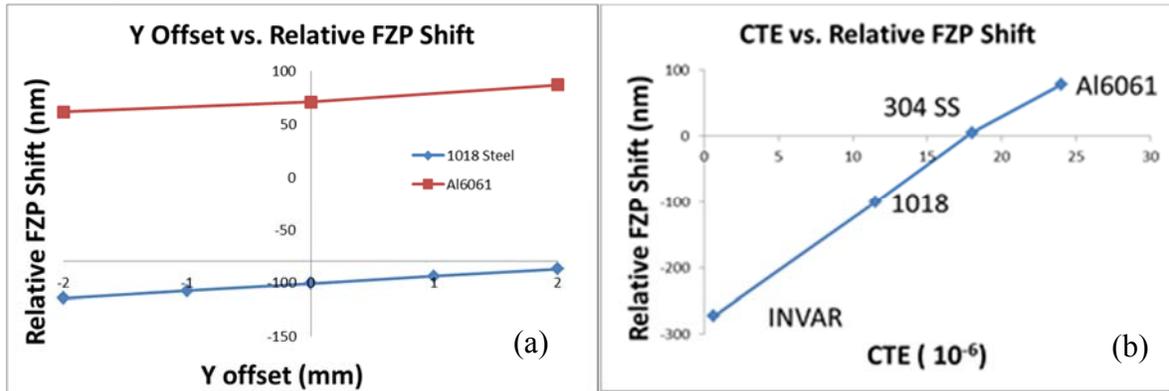


Fig. 2 Z2-33 results (a) Y offset effect on the relative FZP shift for A holder of different materials, and (b) The effect of holder A material CET on the relative FZP shift

SmarAct SLC-1720S stages were used in the assembly. This stage uses a piezo drive that dissipates 25mW when a movement is being performed. The integrated nanometer position sensor will dissipate 4 mW of heat while it is not moving and 170 mW when it is moving. This means that these stages are constantly generating 4 mW of heat even when it is stationary and there is 195 mW of heat being generated during dynamic operation. A static thermal analysis of 4 mW heat generation at the stages and a transient analysis of 2 minutes of stage movement were conducted. The 4 mW of heat generation only causes a temperature rise of 0.014 °C, which corresponds to less than 2nm of lateral displacement and less than 8nm of longitudinal misalignment, which has negligible effect on the overall performance of the FZPs.

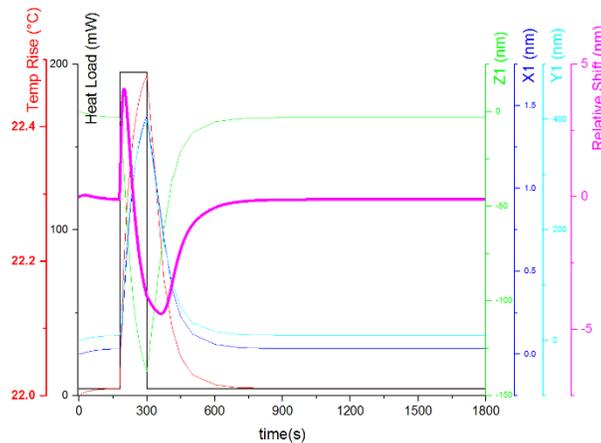


Fig. 3 Time response of Z2-33 to vertical stage move

Transient thermal analyses were carried out to study the effect of heat load due to stage movement. In the transient analyses, a two minute load time of 195mW was applied. Convection cooling by air, with convection coefficient of 150 W/m²·K, was applied on all the exposed surfaces. Fig. 3 shows the time response of Z2-33 to the heat load from the movement of the vertical stage, which is the closest to the 1st FZP and hence the most critical one. The heat generation, temperature rise, x, y, z displacements, and relative FZP shift are shown in the plot. It can be seen that the system temperature and thermal displacements respond instantaneously with the heat from the stage moving. However, FZP will resume

its original place after the stage has stopped moving and the system has cooled down. With air convection cooling, the system will cool down in about 10 minutes from 2 minutes of vertical motor operation.

2. 2 Thermal analysis of Z2-34

Fig. 4 shows the model of Z2-34, the three FZP stacking apparatus, and the FE meshed model. Due to beamline setup restrictions, the structure of Z2-34 is asymmetric. The asymmetric design resulted in comparatively large relative FZP shift between three FZPs. As a consequence, Invar was selected to make the prototype. The analysis results show that the shift in X direction is about 110 nm and in Y direction is about 270 nm for one degree of temperature variation. The relative shifts respond non-linearly with the change of environment temperature, so it is very critical to control the environment temperature when this apparatus is used. More studies need be carried out to optimize the Z2-34 design.

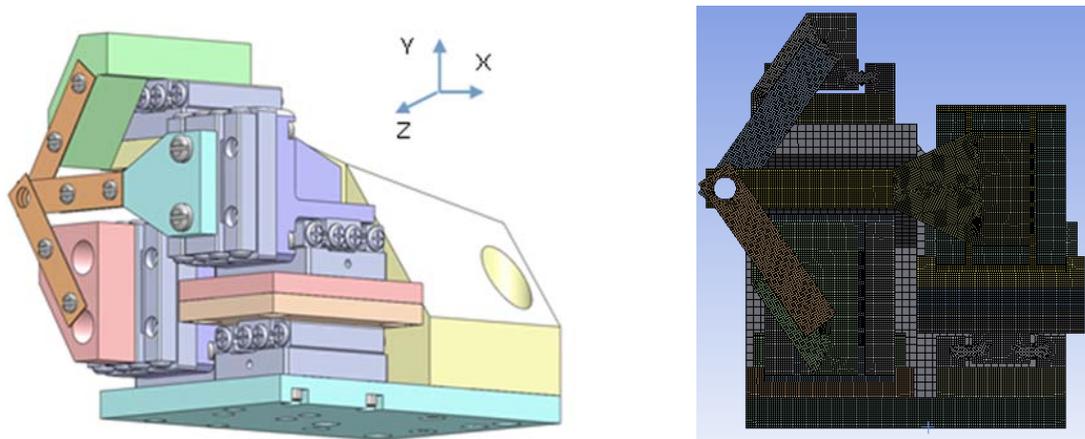


Fig. 4 Z2-34 CAD and FEA models

2. 4. Thermal analysis of Z2-37

Fig. 5 shows the CAD and FEA model of Z2-37, the six FZP stacking apparatus. The apparatus contains 6 identical arms mounted on a hexagon Invar base. Since it is axisymmetric, only one section is analyzed and the results are applied to the other sections through symmetry. In the static analysis of 1°C temperature rise, vertical stages with different offsets were studied to find out the effect of offset on the thermal displacement of zone plates. The thermal displacements of FZP vs. different holder materials were also studied.

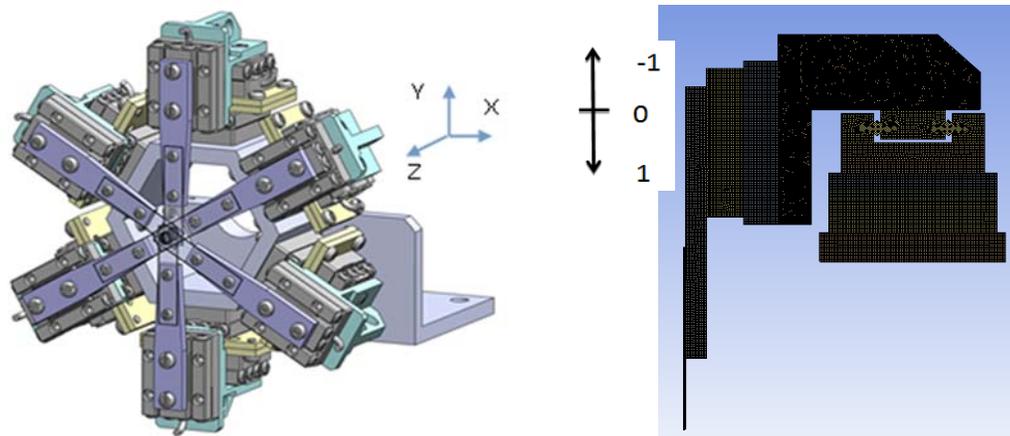


Fig. 5 Z2-37 CAD and FEA model

Fig. 6a shows the Y displacement of the FZP due to 1°C of temperature rise at different Y locations. The analysis was conducted with two different holder materials. It can be seen that Y displacement varies linearly with the offset in Y. Fig. 6b shows the Y displacement changes almost linearly with holder material CTE. From these plots, we can see that by selecting material with appropriate CTE and placing the FZP at appropriate Y location, the thermal displacement in Y direction can be reasonable minimized. In order to estimate the intrinsic error of the FEA software, the same model and analyses were done with three different FEA packages. The different FEA programs were marked on Fig. 6a using error bars. Misalignment of FZPs would result in a decrease of focused flux and focusing efficiency. Depending on the focusing spot size, the misalignment could be in the nanometer scale.

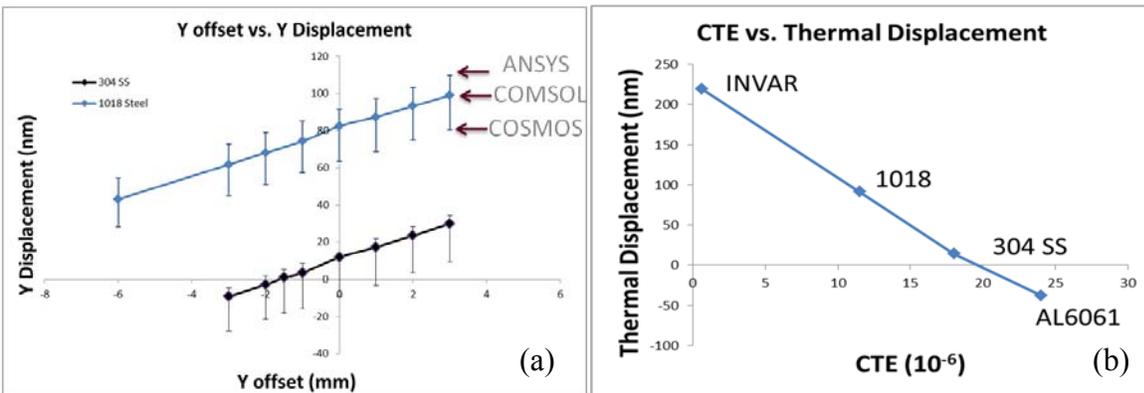


Fig. 6 Z2-37 results (a) Y offset effect on the relative FZP shift for two different holder materials, and (b) The effect of holder material CTE on the relative FZP shift

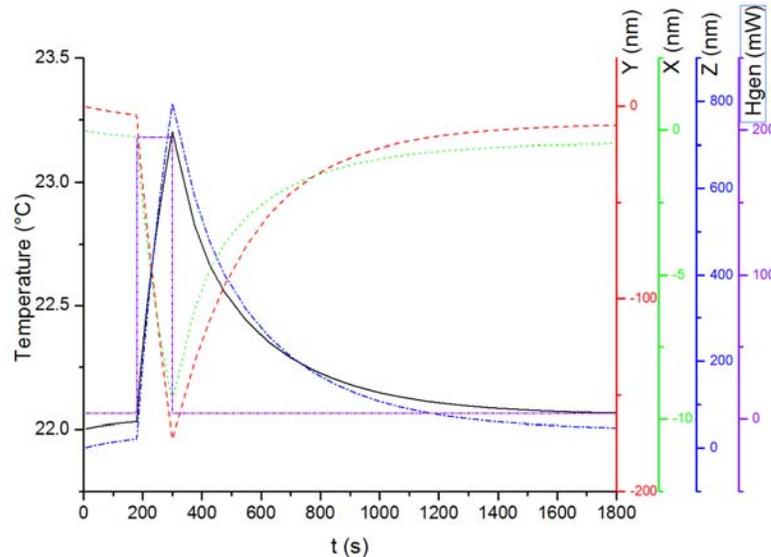


Fig. 7 Time response of Z2-37 to vertical stage move

Fig. 7 shows the time response of the system to the heat load from moving of vertical stage, which is the closest to the FZP and hence the most critical one. The heat generation, temperature rise, and x, y, z

displacements are shown in the plot. It can be seen that the system temperature and thermal displacements respond instantaneously with the heat from the stage moving. However, FZP will resume to its original place after the stage stops moving and the system cools down. With the air convection cooling, the system will cool down in about 20 minutes from 2 minutes of vertical motor operation.

3. Conclusion

The finite element thermal and structural analyses were conducted to study the response of the precision FZP stacking apparatuses to the environmental temperature variation and internal heat load from stages. In the experiment carried out by Gleber et al, the focused flux dropped significantly with a lateral misalignment of 30 nm; and the longitudinal misalignment, depending on the stacked zone plate parameters, can be much bigger than the lateral misalignment (2014). From the analysis results, we can see that Z2-33 and Z2-37 can achieve the required twenty-nanometer focusing size through selecting appropriate holder materials and Y offsets. The system's lateral thermal displacements respond linearly to the temperature variation in the experiment hutch. The standing heat load from the stage causes only negligible thermal displacement. The heat load caused by stage movement is more significant, but the system will resume its original position after the stage stops and the system cool downs. It takes about 20 minutes for the system to cool down to room temperature by air convection cooling. Z2-34 responded more irregularly to the environmental temperature variation and internal heat load due to its unsymmetrical design. In the future, more analysis works need be done to optimize Z2-34 design. Because the stacking accuracy requirement is in tens of nanometer level, reduction of temperature variation in the experiment hutch is critical for the thermal stability of the apparatuses. This is especially true for nanoscale FZP stacking.

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Web sites:

Web-1: <https://www.aps.anl.gov/Upgrade/APS> Upgrade project