ENGINEERING OPTIMIZATION OF THE SUPPORT STRUCTURE AND DRIVE SYSTEM FOR THE LCLS-II SOFT X-RAY UNDULATOR SEGMENTS*

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Abstract

The Linear Coherent Light Source II (LCLS-II) project, an upgrade to the free-electron laser facility at SLAC National Accelerator Laboratory (SLAC), is replacing the undulator system from a fixed gap to two variable gap systems to enable tuning of the photon energy range. The project will include a soft x-ray (SXR) beam line and a hard x-ray (HXR) beam line. The SXR undulators are conventional vertical-gap horizontally-polarizing devices while the HXR undulators are novel horizontal-gap vertically-polarizing devices. This paper describes the development of the SXR mechanical support structure and drive system. The effort has included extensive analysis of the various components to ensure that the undulators will perform within the design specifications. Engineering simulations undertaken and experiments performed to validate the computer modeling are presented together with measurement results from prototype undulators.

DESCRIPTION

The SXR undulator mechanical system, as illustrated in Fig. 1, is composed of an A36 steel frame with four drives mounted to it. The four individual drive assemblies, two left and two right, adjust the gap between upper and lower magnetic structures. Four A514 steel flexure plates are mounted to the drive carriages of the monorail assemblies and to the roller screw assemblies. All four flexure plates are identical. The two aluminum strongbacks are mounted to the flexure plates and finally the magnetic structures are mounted on the strongbacks.

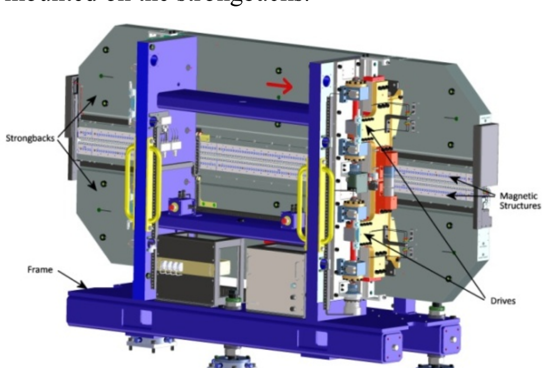

Figure 1: LCLS-II SXR Mechanical System Layout.

The minimum gap between the upper and lower magnetic structure is 7.2 mm and a maximum load of 70 kN on each strongback, due to attraction between magnetic structures is obtained at this gap. At the minimum gap each flexure plate is subject to a 35 kN load with the top flexure plates having an additional constant load of 8kN due to the weight of the strongback and the magnetic structure.

The aluminum strongbacks are mounted to the A36 structural steel frame via A514 steel flexure plates mounted on the drives. This steel was chosen based on the FEA analysis.

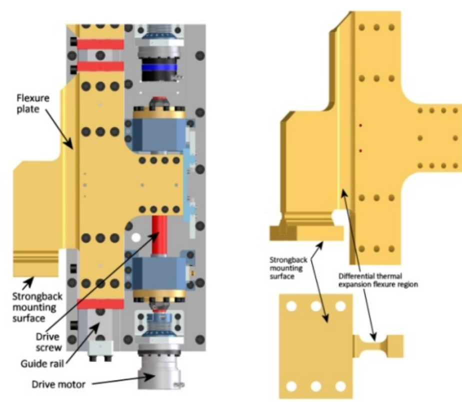

Figure 2: Front view of flexure plate mounted on a bottom drive. The flexure region on each flexure plate allows for differential thermal expansion/contraction between the steel frame and the aluminium strongbacks.

THERMAL CYCLES ANALYSIS OF FLEXURE PLATES

The undulators could potentially experience thermal cycling during storage and transportation with temperatures ranging between 5°C and 35°C (20°C ±15°C).

The temperature in the undulator hall at SLAC will be controlled to a tenth of a degree (20°C ± 0.1°C). A design requirement [1], to guarantee the stability of the magnetic structure and therefore the performance of the undulator, is that after the undulator has been tuned at 20°C it must return to the same tuned state after a thermal excursion and return to 20°C.

Finite Element Analysis (FEA) of the flexure plate was performed to ensure the flexure plates will not yield during thermal cycling. Figure 2 shows the flexure plate differential thermal expansion/contraction flexure region. Figure 3 shows the FEA model of the flexure region with a mesh size of 2 mm.

The FEA results (Fig.4) show that the flexure region elastically deforms with a maximum Von Mises stress

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due to 35°C (+15ºC) and 5°C (-15ºC) of 206 MPa and 254 MPa (Fig. 4) respectively.

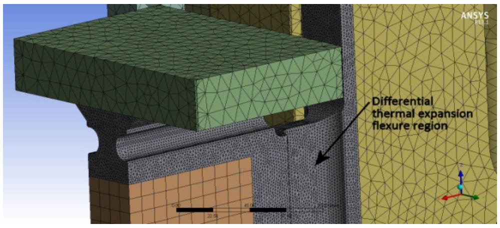

Figure 3: FEA Mesh - Flexure region has a 2 mm mesh.

The flexure material is A514 high strength low alloy steel which has a yield strength of 690 MPa. This gives a safety factor of 3.3 for a temperature excursion to 35ºC and 2.7 for a temperature excursion to 5ºC. The flexure plates will deform in the flexure zone but they should return to their original shape when the temperature returns to 20°C. These results were tested on the prototype undulator.

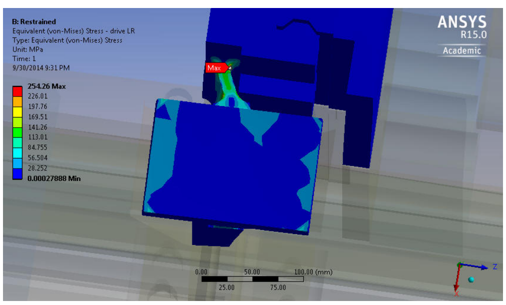

Figure 4: Close-up of the maximum stress of 254 MPa at a temperature of 5°C, located in the lower flexure plate.

ANALYSIS VERIFICATION OF THERMAL CYCLES

The prototype undulator was tuned at 20°C and then subjected to a thermal cycle of ±15°C inside an insulated enclosure. The results of measurements of the second field integrals (trajectories) at 7.2 mm gap before and after thermal cycle show no change due to the changes of temperature (Fig. 5) [2].

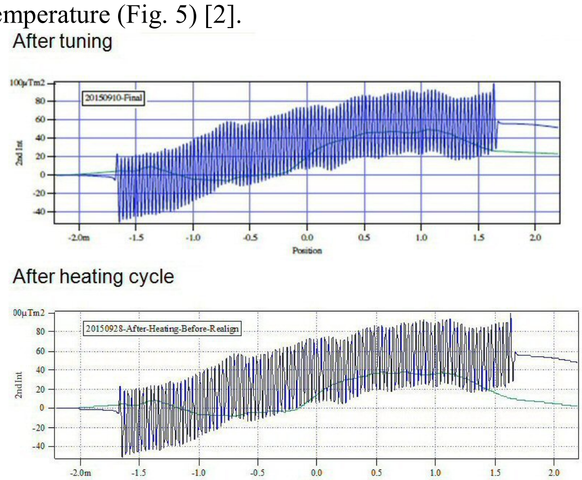

Figure 5: Plot of the second field integrals (trajectories) before and after a thermal cycle from 20°C to 35°C and back.

ANALYSIS OF DRIVE DEFORMATIONS (ROLL) DUE TO MAGNETIC AND GRAVITATIONAL LOADS

The undulator will experience loads of 35kN from the magnetic structure at the minimum gap of 7.2 mm. The Physics Requirement [1] for the maximum roll of the magnetic structure is <4 milliradians (left image of Fig. 6). FEA analysis of the undulator support structure was performed to determine the roll likely to be seen between the upper and the lower drive flexure plate and strongback assemblies.

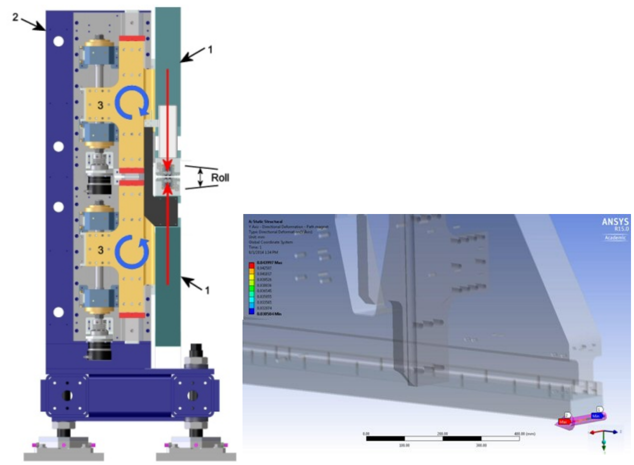

Figure 6: Left image is a end view of undulator showing the drive assemblies. Right image is the FEA analysis result showing the path used to calculate the roll.

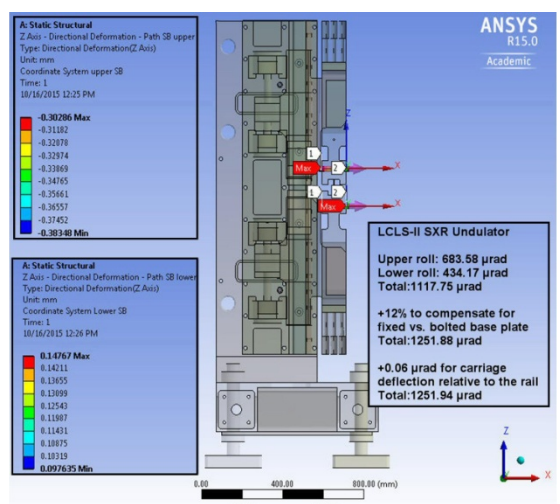

Figure 7: Combined results of the roll between the upper and lower strongbacks.

The other components (i.e. linear rail/carriages, frame and drive base plate all contribute to the roll of the magnetic structures (see left image of Fig. 6 above).

The method used to analyse the roll in the ANSYS FEA model uses a path created on the 120 mm edge of the magnetic structure in the right image of Fig. 6 above. The

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rotation is calculated from the results. This method gives a rotation in the assembly of 1.12 mradian. The drive roll from the carriages is expected to be around 30 µradian per drive. This gives a total roll of 1.25 mradian between the upper and lower magnets. This is well within the 4 mradian requirement.

A verification of the total deflection (roll) was performed on the prototype undulator.

VERIFICATION OF ANALYSIS OF DEFORMATIONS DUE TO MAGNETIC AND GRAVITATIONAL LOADS

The objective of the test is to load the drives to simulate the magnetic load at minimum gap and measure the deflections of various parts of the frame and drive systems. Testing is performed without the magnetic structure. Hydraulic cylinders are used to pull the upper and lower gap drives together. The displacement and rotation of the flexure plates is measured with sensors attached to a separate support frame. The applied force is calculated from pressure gauges showing the pressure in the hydraulic cylinders. The test setup is shown in Fig. 8.

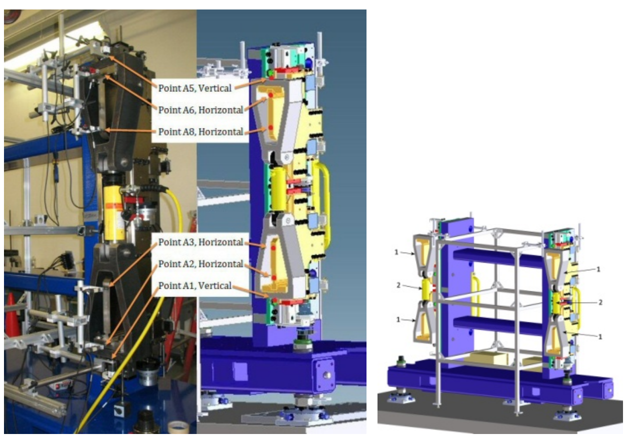

Figure 8: Keyence sensors, shown in the photo on the right, were mounted onto the external frame and touching the flexure plates. The second image shows the gap drive test plates.

Table 1: Load Cycle Test Data

		25%	50%	75%	100%
Load [kN]	0	8.75	17.5	26.25	35
Yaw Top	-1	113	213	351	493
Yaw Bot	3	97	203	334	463
Gap Change [µm]	1.1	-178.8	-347.7	-558.2	-782.5
TOTAL YAW					956

Reset to zero									
0	35	0	35	0	35	0	35	0	35
0	424	3	428	-21	421	-5	438	-5	428
0	409	7	412	-26	412	1	425	-5	426
0	-611.1	-8.4	-619.7	35.1	-626	-2.3	-655.5	-11	-649.8
	833		839		833		863		855
							AVG=	0.845	[mrad]

In Table 1 above the load of 35 kN corresponds to the magnetic forces on one drive when the magnetic gap of the SXR is at the minimum value of 7.2 mm.

Six Keyence contact sensors are used to measure the absolute deflection of the gap drive system at six points as illustrated in the photo in Fig. 8. The six Keyence sensors give the total deflection of the gap drive system since they are mounted onto an external frame that is not exposed to the forces during the gap drive test. The results are shown in Fig. 9. It shows an initial ramp up of the load to let the components settle and then 5 cycles going to full load and back to zero (top and bottom data lay on top of each other). The results show that the drives deflect and return to their original position. The average total roll in this test is 0.834 mrad.

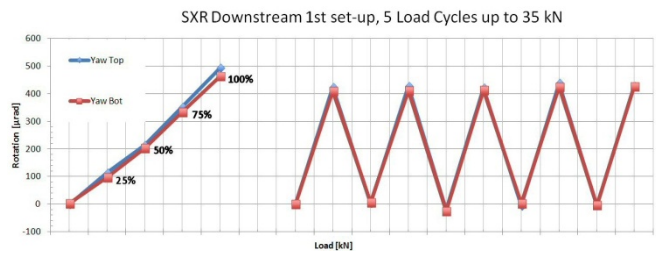

Figure 9: Measured roll of the prototype SXR. The maximum load is 35 kN, which corresponds to the gap drive load for the SXR.

CONCLUSION

The undulator will experience thermal cycling during storage and transportation. The maximum stress in the flexure plates due to differential thermal expansion/contraction will occur during storage and transportation because the undulators could potentially cycle between 5°C and 35°C. The analysis and thermal cycling tests show good agreement with little or no change to the magnetic tuning.

The deflection of the drive system due to the magnetic and gravitational loads was analyzed and also verified with a test on the prototype undulator. The drive did deflect but when the pressure was removed the drive components returned to the original position.

REFERENCES

[1] Heinz-Dieter Nuhn, "LCLS-II Undulator System Physics Requirement", SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA, Rep. Physics Requirements Document LCLSII-3.2-PR-0038-R2.

[2] E. Wallén and A. DeMello, "HXU Prototype Gap Drive System Deflection Test", Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA, Rep. Engineering Note 11043.