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OVERALL PROGRESS ON DEVELOPMENT OF X-RAY OPTICS MECHANICAL SYSTEMS AT HIGH ENERGY PHOTON SOURCE (HEPS)

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Abstract

High Energy Photon Source (HEPS) regarded as a new 4th generation synchrotron radiation facility, is under construction in a virgin green field in Beijing, China. The X-ray optics/mirror mechanical systems (MMS) play an important role, which would be expected to be designed carefully and rigidly for the extremely stable performance requirement of HEPS. In addition, there are indeed big challenges due to so many types of mirror systems, such as white beam mirror (WBM), harmonic suppression mirror (HSM), combined deflecting mirror (CDM), bent mirror, Nano-KB, and the transfocator of Compound refractive lens (CRLs), etc. Therefore, overall progress on design and manufacture of the MMS is introduced, in which a promoting strategy and generic mirror mechanical system as a key technology is presented and developed for the project of HEPS. Furthermore, ultra-stable structure, multi-DOF precision positioning, Eutectic Gallium Indium (E-GaIn)-based vibration-decoupling water-cooling, clamping, and bending have always been prior designs and considerations.

INTRODUCTION

To meet the extreme requirement of 4th generation synchrotron radiation facility, many efforts and design considerations on the X-ray optics mechanical system are presented, such as an ultra stability mirror system or benches [1-7], a better mounting and water-cooling of mirror [8], and an improved bender [9].

HEPS is a new and under construction 4th generation synchrotron radiation facility. It has a 6 GeV storage ring with a circumference of 1360.4 m and a natural emittance of 34.2 pm [10]. The ground stability of vibration should be required to 25 nm @1~100 Hz. So, the stability of mechanical engineering design of synchrotron instrument and device becomes a critical important issue. Besides, there are 15 beamlines in Phase I of HEPS, which has so many types of mirror systems, such as white beam mirror (WBM), harmonic suppression mirror (HSM), combined deflecting mirror (CDM), bending mirror, Nano-KB, and the transfocator of Compound refractive lens (CRLs), etc. This bring out another big challenge. So, to deal with the problems, a promoting strategy is presented at HEPS. The steps as follows: firstly, a high-performance generic mirror mechanical systems (GMMS) is first proposed and developed. Secondly, GMMS-based variable mirror mechanical system or Transfocator will be designed and manufactured. Actually, GMMS would been also applied for the main mechanical system of Laue double bent crystal monochromator (LDBM). Finally, lots of specific mechanical designs in vacuum will be implemented, including bender, water cooling, support and clamping, and other custom-made mechanisms.

OVERALL DESIGN STRATEGY

It is well known that base support, positioning, and clamping are the three common main functions of the mirror mechanical system (MMS), although the types of MMS are different. So, a high-performance MMS is presented and developed, which not only features ultra-stable, bust also has a high accuracy attitude adjustments and stress-free mirror mounting. More importantly, it is expected to be a generic MMS (GMMS) for a large number and variety mirrors at HEPS. Therefore, a strategy of GMMS is proposed as shown in Fig. 1. Moreover, a customized GMMS-based design scheme will be formed as shown in Fig. 2.

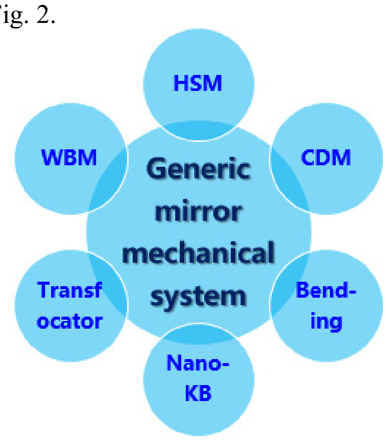

Figure 1: The promoting strategy of design for MMS.

Compared to the existed mirror mechanical systems, the vibration stability of ≤ 25 nrad rms@1-120 Hz and 5-DOF positioning-motorized are extracted as the main technical parameters of GMMS. And it must be compatible for horizontal reflection mirror and vertical reflection mirror as shown in Fig. 3. It is that the performance of yaw adjustment mechanism is equivalent to pitch. Be-

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cause the yaw angle of the horizontal reflection layout is same to the pitch of the vertical for the same system. Correspondingly, the pitch of the horizontal is also same to the yaw of the vertical.

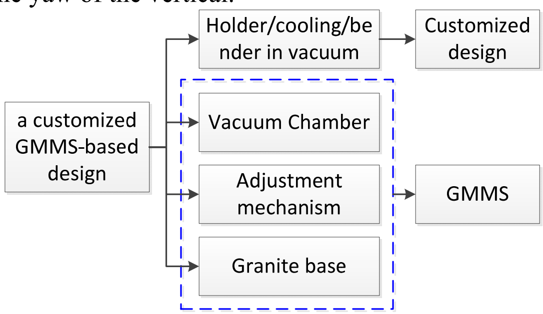
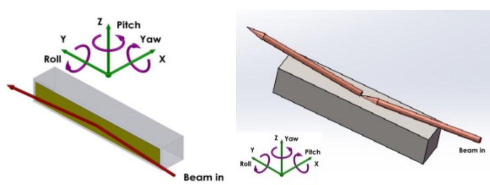


Figure 2: A customized GMMS-based design scheme.



(a) (b)

Figure 3: Layouts of horizontal and vertical reflection mirrors. (a) Horizontal reflection. (b) Vertical reflection.

GMMS DESIGN

According to the standard coordinate system defined by HEPS beamlines as shown in Fig. 3, the main parameters of 5-DOF is shown in Table 1.

Table 1: Main Parameters of 5-DOF for GMMS

	Parameter	Resolution	Range	Type
1	Horiz.Translation (Tx)	≤ 1 μm	±10 mm	motorized
2	Vert. Translation (Tz)	≤ 1 μm	±10 mm	motorized
3	Horiz.angle (Rz)	≤ 0.1 μrad	±10 mrad	motorized
4	Vert.angle (Rx)	≤ 0.1 μrad	±10 mrad	motorized
5	Roll (Ry)	≤ 10 μrad	±17.5 mrad	motorized

To ensure adequate stiffness, the overall mechanical structure of GMMS based on the combination of a multi-layer granite adjustment mechanism and a double-disc flexure hinge angle mechanism is designed. As shown in Fig. 4, the multi-layer granite adjustment mechanism can provide 4-DOF with motorized type in air of Tx, Tz, Rx, and Ry. The granite wedges lift based on sine bar method are employed for adjustments of the height Tz and angle Rx instead of the traditional cantilever support structure. Self-locking is another key point used for each DOF to guarantee the static stiffness and stability. Besides, the simplified double-disc flexure hinge angle mechanism can realize the other degree of Rz with a PiezoMotor in vacuum. The monolithic flexure hinge is designed as shown in Fig. 5, which can be cut by slow wire processing. It has a higher stiffness than by assembling. By FEA-modal simulation, the mechanical structure has been optimized and many times iteration designed, which has an adequate 1st mode eigenfrequency, as shown in Fig. 6.

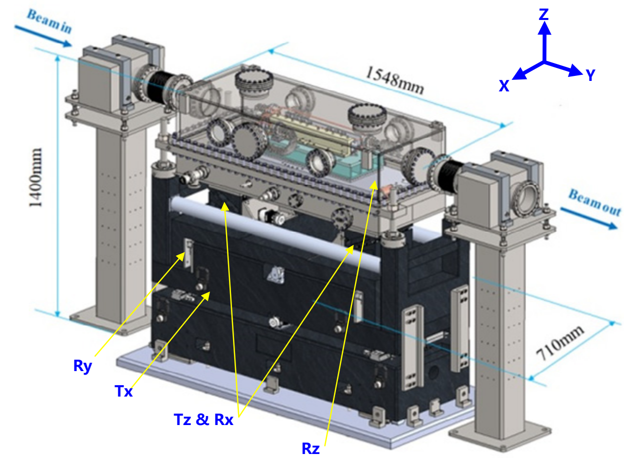


Figure 4: The overview of the typical design of GMMS.

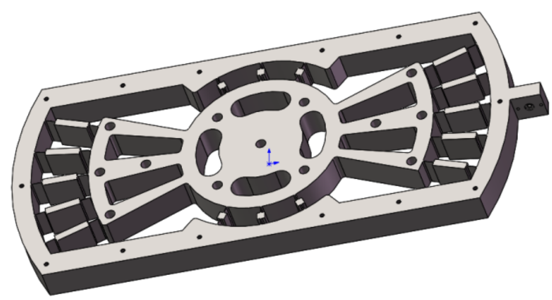


Figure 5: Monolithic flexure hinge.

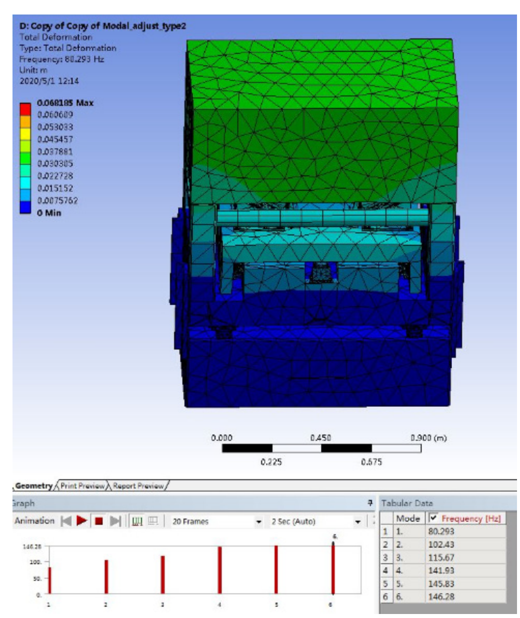


Figure 6: FEA-Modal simulation.

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A CUSTOMIZED GMMS-BASED DESIGN

As is mentioned above, specified mechanical structure in vacuum need to be a customized GMMS-based designed, especially bender, watercooled & mounting assembly unit.

Firstly, independent four-shaft bending with gravity association design method is presented by Prof. Ming Li at HEPS. Based on the method, the high stiffness bender is customized designed, as shown in Fig. 7. It performs higher stiffness and stability than thin or leaf spring type bender although it takes up more space in the mirror ends.

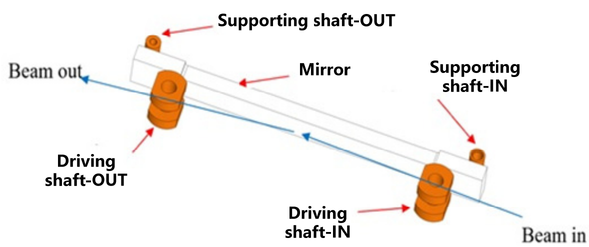
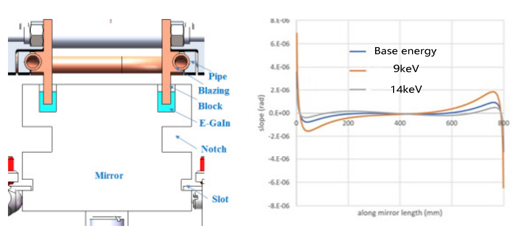


Figure 7: Principle diagram of an independent four-shaft bending.

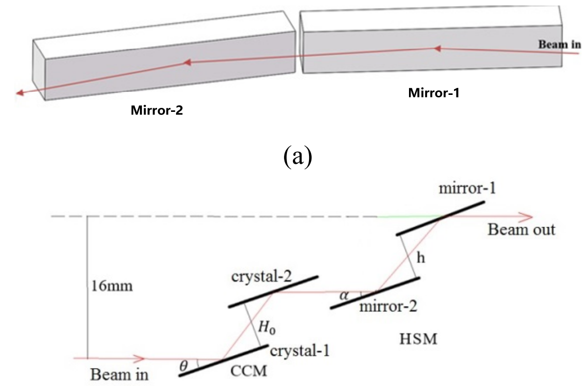
Secondly, a bath watercooled structure filled eutectic Ga-In alloy is designed for the white beam mirror with non-bent or bent. It can overcome the problem caused by the vibration impact of fluid and the water pipes in the case of ensuring sufficient cooling capacity. As shown in Fig. 8, mirror slope error can be controlled based on geometrical optimized by FEA for different heat load or variety energy. Furthermore, In order to avoid corrosion effect between Eutectic Ga-In alloy and heat sink metal for X-ray optics cooling, a novel coating of tungsten (W) is presented and developed at HEPS [11].



(a) (b)

Figure 8: Principle diagram of a bath watercooled structure filled eutectic Ga-In alloy. (a) Structure. (b) Thermal deformation controlled based on geometrical optimized by FEA.

Thirdly, the clamping and combination of double mirrors system, as a specified structure, has also considered and developed, which is usually need by CDM and HSM, as shown in Fig. 9. For the former, clamping and mechanical combination positioning need to be carefully considered. And for the latter, it is not only the mounting and fixing quasi-static structure of traditional parallel double mirrors, but also needs the kinetic design of the fixed exit height similar to the T-type compensation mechanism of monochromators, as shown in Fig. 9 (b).



(a)

(b)

Figure 9: Principle diagram of the double mirrors system. (a) CDM. (b) Complicated HSM for the height compensation of the channel cut mono. (CCM) at B8-XAS beamline.

Finally, transfocator, a switch mechanism of CRLs regarded as an effective high energy X-ray component is developed. In traditional design, N sets of motors or actuators for the motion and state switch of the N arms in which each arm is as a stack filled CRLs. It looks bulky and inflexible when N becomes larger due to the series structure. To deal with this problem, a compact transfocator by the parallel driving structure is presented, as shown in Fig. 10. It just employs 2 sets for N arms, which has a simplified & stable structure and a longer work distance.

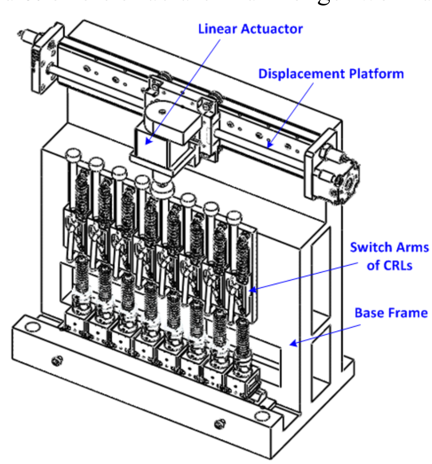


Figure 10: A compact transfocator.

Besides, an in-vacuum motion mechanism similar to the above HSM is designed for the LDBM of B1-EM beamline. This is so that the GMMS can also be applied here.

MANUFACTURE, ASSEMBLY, AND TEST

Now, the first GMMS, as the application of BE-WBM, has been manufactured and delivered in December 2022. It is not only a pure GMMS, but also has a customized watercooled mirror clamping. It is proved to be effective and feasible by assembly and test.

Than, the 9 sets of GMMS as first batch has been manufactured and delivered in July 2023. FAT passed

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smoothly that indicates the design, manufacture, and assembly are mature and available, as shown in Fig. 11. And the next step is to finish manufacturing the second batch (10 sets) in the middle of next year.

Figure 11: FAT pictures of first batch of GMMS.

So, the GMMS can be evolved or directly applied for many kinds of mirrors, e. g. the white beam mirror (WBM) or WBM-bender, harmonic suppression mirror (HSM), combined deflecting mirror (CDM), bent mirror, Nano-KB, and the transfocator of Compound refractive lens (CRLs), etc. As shown in Table 2. There are the total 20 sets of GMMS and customized MMS. Therefore, the challenge will be derived from mirror installation and transportation which need many rigid and careful considerations.

Table 2: Beamlines Optics/Mirrors at HEPS Phase I

Beamline	Optics/mirror	Quantity
B1-EM	LDBM	1
B2-NAMI	WBM-bender Transfocator	2
B3-SDB	Transfocator	1
B5-HX-HERS	WBM	1
B6-HPB	Transfocator	1
B8-XAS	WBM-bender Bent mirror HSM	3
B9-LODISP	Transfocator 1 Transfocator 2	2
BA-MX	Transfocator	1
BB-pink-SAXS	CDM	1
BC-high-NESS	Bent mirror	1
BD-TEX	WBM-bender Bent mirror HSM	3
BE-TXM	WBM Bent mirror	2
BF-TB	Bent mirror-TF	1
	Total:	20

CONCLUSION

A promoting strategy of MMS is presented for the development of large quantity and variety type optomechanical systems. And the corresponding conclusions are as follows:

1) A customized GMMS-based design strategy has been implemented for beamlines at HEPS, in which generic and specific are both effectively considered.

2) Progress on GMMS manufacturing and assembling imply that an ultra-stable and 5-DOF mechanical system is achievable and fine so that the first batch has been already delivered.

3) The various mirror benders or clamping & water-cooling or special-mechanisms in vacuum are also smooth in process of design and fabrication.

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