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MECHANICAL DESIGN OF MULTILAYER KIRKPATRICK-BAEZ (KB) MIRROR SYSTEM FOR STRUCTURAL DYNAMICS BEAMLINE (SDB) AT HIGH ENERGY PHOTON SOURCE (HEPS)

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Abstract

SDB aims in-situ real-time diagnosis in dynamic compression science and additive manufacturing. Nano-experimental environment requires highly multilayer KB mirror system in thermal deformation and stability of mechanism. This paper illustrates the KB cooling scheme and mechanical design. Only using variable-length water cooling to control the temperature and thermal deformation of mirror has limitations here. First, the installation of cooling system should be non-contact so that the surface shape can be sophisticatedly controlled without deformation of chucking power. Second, the distance between the HKB and the sample stage is too small to arrange the cooling pipe. Third, the KB mirror has multi-dimensional attitude adjustment. Cu water cooling pipe would be dragged with adjustment thus it has to be bent for motion decoupling, which occupies considerable space. Thus, the Cu cooling block and water cooling pipe are connected by copper braid. Eutectic Gallium-Indium fills a 100 µm gap between the cooling block and KB mirror to avoid chunking power deformation. Finally, the structural stability and chamber sealability are analyzed.

INTRODUCTION

Structural Dynamic Beamline (SDB) at High Energy Photon Source (HEPS) [1] intends to realize in-situ real-time diagnosis of dynamic and non-reversible processes in dynamic compression science and additive manufacturing fields [2]. The beamline station includes a micro-beam hutch, a large-spot hutch, and a nano-beam hutch. The multilayer Kirkpatrick-Baez (KB) mirror system is located at the last nano-beam hutch, which focuses the secondary source at 95.5 m on 210 m to form a 60 nm light spot. The nano experimental environment requires multilayer KB mirror system highly since any chunking power or thermal source would deform the KB mirror surface shape. The mechanical structure of multilayer KB mirror system was meticulously designed, especially the cooling scheme. Water or liquid nitrogen [3] cooling with oxygen-free high-conductivity (OFHC) copper braid [4] or copper stripe [5] is a common method for beamline station equipment, such as Fresnel zone plates (ZP) microscope modules [6] and monochromators [7]. Considering the installation space limitations and the surface shape requirement of the KB mirror, a water cooling scheme combining copper braids and eutectic GaIn [8] was utilized to remove thermal load. Deep calculation and finite element analysis (FEA) have been operated.

The remaining parts of this paper are organized as follows: Section 2 gives the overview of mechanical structure design. Section 3 depicts the cooling scheme and thermal ansys results. The conclusions are reported in Section 4.

MECHANICAL STRUCTURE DESIGN

The overview of mechanical structure design is shown in Fig. 1. The length, width, and height of the whole KB mirror system are 1430 mm, 740 mm, and 1150 mm respectively. The size of horizontal Kirkpatrick-Baez (HKB) is 70 mm×40 mm×50 mm and of vertical Kirkpatrick-Baez (VKB) is 120 mm×40 mm×40 mm. Except for the KB mirror, the multilayer KB mirror system includes pose adjustment mechanism, a gantry, and cooling system. The fishbone flexure hinge and U-frame flexure hinge mechanism are used for position and attitude adjustment respectively, which fulfill the movement requirement in Table 1. The granite air-bearing table outside the chamber controls the whole KB mirror system moving in X and Z-axis directions.

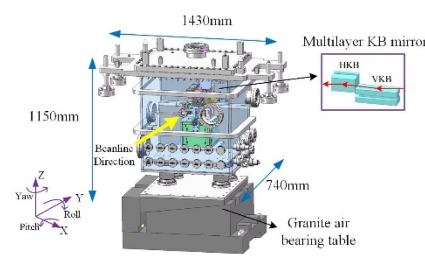

Figure 1: The mechanical structure.

Table 1: Adjustment Parameter Index for HKB, VKB, and Whole KB Mirror System

	Movement	Resolution	Range
HKB	X-axis	1µm	±0.5mm
	Yaw	1µrad	±10mrad
VKB	Z-axis	1µm	±0.5mm
	Y-axis	1µm	±0.5mm
	Pitch	1µrad	±10mrad
	Roll	10µrad	±20mrad
Whole System	X-axis	1µm	±5mm
	Z-axis	1µm	±5mm

A stable invar gantry shown in Fig. 2(a) is designed for metrology and to solve the problem of the limited installation space for HKB. By lightweight design, the gantry mass is only 188.3 kg. The granite stage is sufficiently stiff to not amplify vibrations. In FEA modal simulation, the resonance frequency is over 140 Hz. The first modal analysis and the direction of rigid motion are performed in Fig. 2(b). To avoid interference with the sample stage, the

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design of a special-shaped KB vacuum chamber is shown in Fig. 2(c). The max deformation of sealing surface is less than 0.05 mm in Fig. 2(d). The mechanical design is considered feasible.

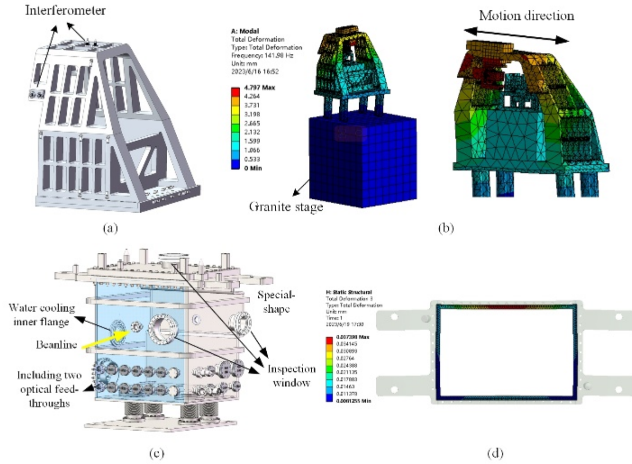

Figure 2: (a) The structure of the gantry. (b) FEA simulaiton result of gantry. (c) Mechanical structure of KB vacuum chamber. (d) Deformation of the sealing face.

COOLING SCHEME

By efficient thermal deformation optimization iteration analysis, a variable-length water cooling scheme was adopted [9]. The distribution of Cu cooling block of HKB and VKB is shown in Fig. 3.

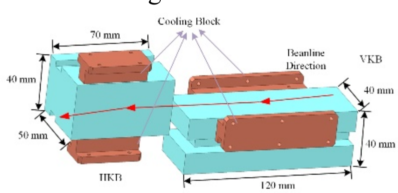

Figure 3: The distribution of Cu cooling block of HKB and VKB.

There are two things to note. First, the Cu cooling block design of HKB is very close to the sample stage. The distance between the HKB mirror and the sample stage is too small to arrange copper pipe and window flange. Besides, the VKB has a four-dimensional attitude adjustment. The copper pipe would be dragged with adjustment thus it has to bend for motion decoupling, which occupies considerable space in the chamber. To solve the two issues above, the Cu cooling block and cooling copper pipe are connected by copper braids. Second, the Cu cooling block should be in non-contact with KB mirror so that the surface shape would not be deformed by chucking power. Hence, a 100 μm gap between the cooling block and KB mirror is reserved, which is filled with eutectic Gallium-Indium (eGaIn). The eGaIn has a good thermal conductivity, whose thermal conductance is larger than 10^5 W/(m^{2}K). Therefore, a cooling scheme of copper braid & eGaIn is proposed. The mechanical structure of cooling part is shown in Fig. 4, which consists of HKB and VKB Cu cooling block, cooling pipe, copper braids, and a mask. The mask protects the mirror from the X-ray source.

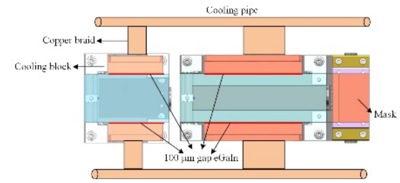

Figure 4: The mechanical structure of the cooling part.

Thermal Deformation Simulation

The cooling effect of copper braids with different thicknesses was analyzed. Four groups of simulations are conducted, including three groups with 2 mm, 5 mm, and 10 mm copper braids, and one group without. Through the same thermal power density distribution, the steady-state thermal simulation results are summarized in Table 2.

Table 2: The Simulation Temperature Results of Different Cooling Designs

Copper braids	HKB (°)		VKB (°)	
	Max	Difference*	Max	Difference
Without	25.160	0.114	25.662	0.501
10 mm	25.337	0.122	26.054	0.511
5 mm	25.435	0.124	26.426	0.521
2 mm	25.714	0.126	27.503	0.530

*The surface max difference temperature.

The max and max surface difference temperature of HKB and VKB is increased with decreasing thickness of copper braid, while too thick copper braids will put a burden on the mechanical structure. Hence, the cooling scheme of the copper braids with 5 mm thickness is utilized, and the thermal transient analysis of this scheme is given. The period of the heat source is 100 ms and the duty ratio is 0.2. In the simulation, the max temperature variation with time is shown in Fig. 5.

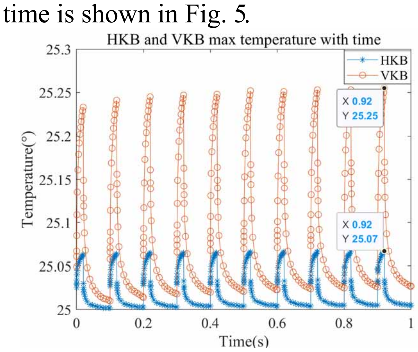

Figure 5: The variation of the max temperature in HKB and VKB surfaces with time.

In a period cycle, the max temperature values of HKB and VKB are about 25.07° and 25.25° respectively. Considering the mirror fix method, the thermal deformation difference on HKB and VKB mirror surface between the peak and valley (PV) situations is given in Fig. 6(a) and (b). According to Fig. 6, the thermal deformation pv difference on the meridional plane is shown in Fig. 7. The PV value of HKB is 0.11 nm and of VKB is 0.60 nm, which fulfills the experimental requirement.

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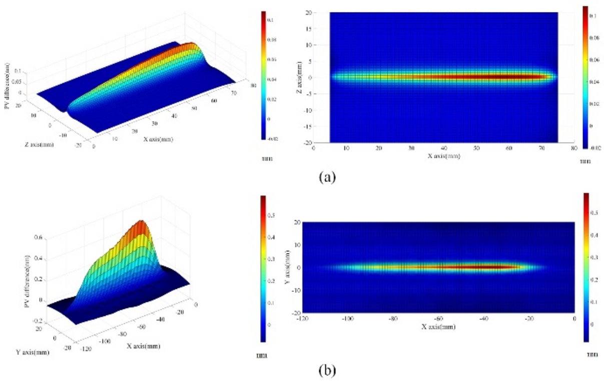

Figure 6: The thermal deformation PV difference on the mirror surface of HKB (a) and VKB (b).

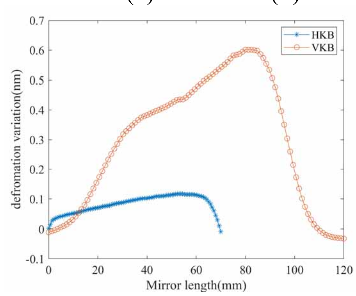

Figure 7: The thermal deformation PV difference at the meridional plane

Stress Analysis of Copper Pipe

Though the copper braids can decouple the motion of KB mirrors, the copper pipe still has to be bent for the two-dimensional movement of the whole equipment system. The cooling system is installed on the gantry. The water cooling outlet is connected to the outer chamber by a flange. When the whole KB equipment is adjusted, the gantry moves relative to the chamber. The X-axis and Z-axis movement range are both -5 to 5 mm. Therefore, the shape of the copper pipe is designed in Fig. 8(a). The maximum compound displacement of the X-axis and Z-axis is load in simulation and the static structural analysis is shown in Fig. 8(b). The max equivalent stress is 57 MPa, whose position is at a clamping point. Therefore, this bend design of copper pipe is optimized. The cooling design is not complex and space-occupying.

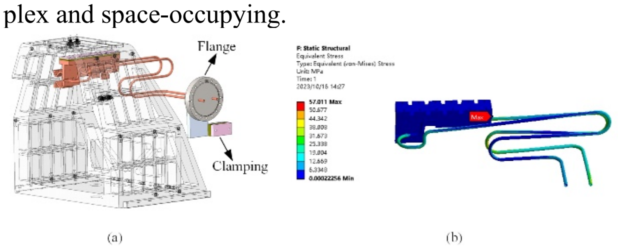

Figure 8: (a) The mechanical design of the cooling system. (b) The static structural analysis.

Mask Design

The mask is installed before the VKB in Fig. 9(a). In the simulation, a five times heat flux is loaded on the mask bevel. The result shows that the thickness of copper braids connected with the mask should reach 5 mm so that the max temperature of the mask surface, 257° in Fig. 9(b), does not exceed the melting point of OFHC.

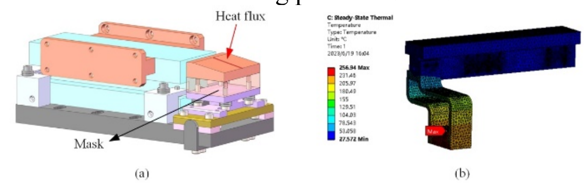

Figure 9: (a) The installation of the mask. (b) The steady-state thermal simulation result of the mask.

CONCLUSION

In this paper, the mechanical structure of multilayer KB mirror system for SDB at HEPS is designed. According to practical engineering cases, the water cooling system is adjusted. The structure and thermal FEA simulation is given. The analysis results fulfill the requirement. The KB mirror system will soon be in process and go into service.

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