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DESIGN AND TESTING OF HEPS STORAGE RING MAGNET SUPPORT SYSTEM

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Abstract

Very low emittance of High Energy Photon Source (HEPS) demands high stability and adjusting performance of the magnet support. The alignment error between girders should be less than 50 µm. Based on that, the adjusting resolution of the girder are required to be less than 5 µm in both transverse and vertical directions. Besides, the natural frequency of magnet support system should be higher than 54 Hz to avoid the amplification of ground vibrations. To fulfill the requirements, during the development of the prototype, the structure was designed through topology optimization, static analysis, grouting experiments, dynamic stiffness test and modal analysis, and the rationality of the structure was verified through prototype experiments. During the tunnel installation, the performance of the magnet support system was again verified to be better than the design requirements through test work after installation.

INTRODUCTION

HEPS storage ring consists of 48 modified hybrid 7BA achromats. The circumference is 1360.4 m and each arc section is about 28 m. HEPS is designed with very low emittance of less than 60 pm·rad to provide much brighter synchrotron light. Precise positioning and stable supports of the magnets are required.

The alignment error between magnets on a girder should be less than 30 µm in horizontal and vertical direction, and that between girders should be less than 50 µm. Also, natural frequency of magnet support system should be higher than 54 Hz to decrease amplification of ground vibrations, which is very challenging. The requirements are listed in Tables 1 and 2 [1].

Table 1: Alignment Tolerance

Tolerances	Magnet to Magnet	Girder to Girder
Transverse	±0.03 mm	±0.05 mm
Vertical	±0.03 mm	±0.05 mm
Longitudinal	±0.15 mm	±0.2 mm
Pitch/yaw/roll	0.2 mrad	0.1 mrad

Table 2: Requirements for Support System

Parameter		Value
Resolution	Transverse	⩽ 5 µm
	Vertical	⩽ 5 µm
	Longitudinal	⩽ 15 µm
Natural frequency		⩾ 54 Hz

According to the layout of the magnets, there are 6 support units for the multipoles in each arc section, including 2 FODO modules, 2 MULTIPLET modules and 2 QDOUNLET modules, as shown in Fig. 1. The adjacent multipoles share one girder and are seated on the plinths through adjustable wedge mechanisms, while the 5 longitudinal dipoles are bridged between the plinths.

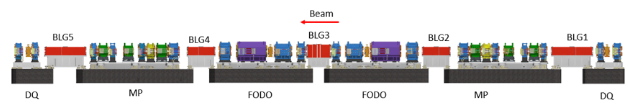

Figure 1: One arc section(1/48).

Stringent alignment accuracy requests high adjusting resolution of the girders. Table 2 shows the requirements. The resolution should be better than 5 µm in transverse and vertical directions and 15 µm in longitudinal direction.

DESIGN OF THE SUPPORT SYSTEM

The support system is designed as Fig. 2 shows. The girder should be capable of moving in 6 dimensions and the adjusting mechanisms are designed with 6 sets in vertical direction, 2 sets in transverse and 1 set in longitudinal direction. Each magnet is supported by a special adjusting mechanism to realize the three-direction adjustment, in which the sextupole is supported by the mover, which is able to realize the online adjustment.

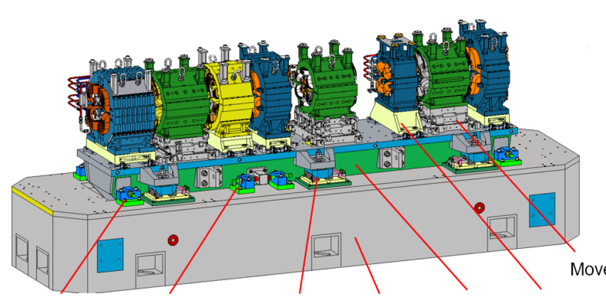

Figure 2: Support system.

Girder Body

After pre-simulation optimization [2], the effects of different structural parameters of the girder body on its deformation and natural frequency are analyzed, and the optimal stiffness is obtained by optimizing the shape of the cross-section and the distribution of the stiffeners. The structure of

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the girder body is a six-point support box structure as shown in Fig. 3, and the material is HT350, which has higher structural damping, less residual internal stress, and more stable long-term dimensions.

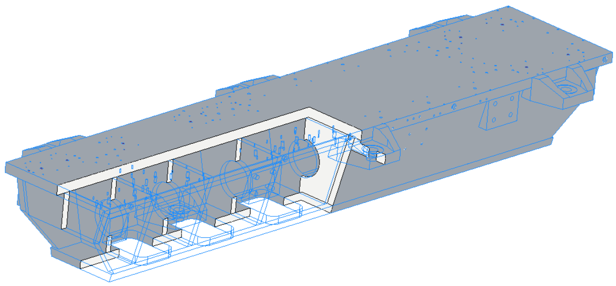


Figure 3: Girder body.

Plinth

With the advantages of good stability and low cost, concrete plinth is adopted by many synchrotron accelerators [3, 4]. The normal Elastic modulus of concrete is about 30 GPa, which is relative low to resist deformation. So high Elastic modulus recipe was developed and the sample achieved 53 GPa. The plinth is a reinforced concrete precast structure, which is designed to be groove shape to match the girder installation, as shown in Fig. 4.

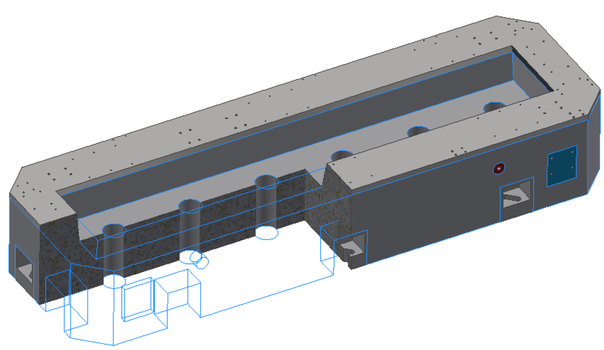
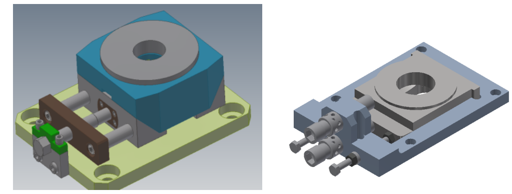


Figure 4: Plinth.

Support Components

In order to fulfill the pre-alignment and stability requirements, the support system is hierarchical adjusted of girder and magnets. High stiffness wedges are used as mechanisms for supporting and vertical motion, as shown in Fig. 5. The top surface of the wedge is equipped with a spherical disc to compensate for the angle change during alignment operation and keep contact of the interface. It is beneficial to guarantee the stiffness and avoid joint stress.

Sextupoles in the storage ring of HEPS will be adjusted based on beam trajectory. The mechanical design of a beam-based alignment sextupole mover should be developed. The motion accuracy of the mover should be better than 5 µm under 450 kg load of sextupoles. After preliminary prototype development, the structure of the mover was finalized as a 3-layer sliding wedge structure [5]. The movement range



(a) Girder body adjustment (b) Magnet adjustment

Figure 5: Vertical adjustment.

is required to be ±0.3 mm in both horizontal direction and vertical direction.The yaw and roll should be less than 3”, and the pitch should be less than 2”. The horizontal displacement during vertical movement, which is called coupled error, should be less than 15 µm.

TEST OF THE SUPPORT SYSTEM

Plinth Grouting Experiment

In order to analyze the effect of foundation dimensions and grouting process on the natural frequency of the plinth, finite element simulation is used to compare and analyze the simulation and measured results for each working condition. The modal analysis module of finite element software is used to simulate the test results of different working conditions by taking the elastic foundation stiffness coefficient as the only variable. It should be added that: in the case of the same foundation, the size of the stiffness coefficient reflects more the influence of different connection method, in the case of the same connection method, the size of the stiffness coefficient reflects the influence of the foundation dimensions.

According to the experimental and simulation results of different working, the following conclusions are obtained: (1) with the same foundation and different connection methods, the epoxy secondary grouting results have higher stiffness coefficients and higher measured results, as shown in Fig. 6. (2) with the same epoxy secondary grouting method, different foundation dimensions, the area of the foundation and the thickness of the foundation have an effect on the stiffness coefficients, as shown in Fig. 7. (3) in the same foundation, the epoxy secondary grouting connection method has good repeatability, as shown in Fig. 8. Finally, the secondary

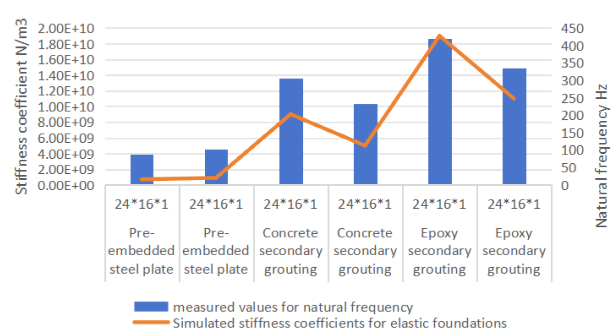


Figure 6: Same foundation dimensions and different connection methods.

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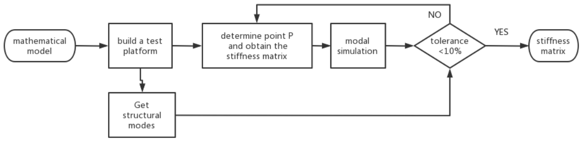


Figure 7: Flow chart.

$$\begin{bmatrix} m & & & & mR_{cp,z} & -mR_{cp,y} \\ & m & & -mR_{cp,z} & & mR_{cp,x} \\ & & m & mR_{cp,y} & -mR_{cp,x} & \\ & -mR_{cp,z} & mR_{cp,y} & I_{xx,p} & & \\ mR_{cp,z} & & -mR_{cp_x} & & I_{yy,p} & \\ -mR_{cp,y} & mR_{cp,x} & & & & I_{zz,p} \end{bmatrix} \begin{bmatrix} \ddot{x}_p \\ \ddot{y}_p \\ \ddot{z}_p \\ \ddot{\theta}_x \\ \ddot{\theta}_y \\ \ddot{\theta}_z \end{bmatrix} = \begin{bmatrix} K_{xx} & & & & & \\ & K_{yy} & & & & \\ & & K_{zz} & & & \\ & & & K_{\theta_x\theta_x} & & \\ & & & & K_{\theta_y\theta_y} & \\ & & & & & K_{\theta_z\theta_z} \end{bmatrix} \begin{bmatrix} x_p \\ y_p \\ z_p \\ \theta_x \\ \theta_y \\ \theta_z \end{bmatrix}$$

Figure 8: Stiffness matrix equation.

grouting method of epoxy-based grout was determined as the connection method between the storage ring plinth and the ground.

Modal Test

Free boundary constrained modal testing of the plinth, together with simulation is able to back-calculate the modulus of elasticity and thus assess the construction quality of the pedestal. The free boundary constraint modal design requirements for the plinth are shown in the Table 3.

Modal testing of grouted plinths is necessary during the bulk installation process to detect problematic plinths in time for timely treatment. The modal design requirements for grouted plinths are shown in the Table 3.

All the plinths are measured and the results fulfill the design requirements. The simulation and measurement results match well.

Support Components

The stiffness of the support components has an important influence on the stability of the support system, and the accuracy of its value determines the accuracy of the modal simulation results. Through the dynamic stiffness test, the stiffness matrix of the girder and magnet vertical adjustment mechanism is obtained, so as to get an accurate simulation model of the support system, which in turn provides conditions for the subsequent structural modification.

Test Method

Based upon rigid-body dynamics and frequency response function measurements, the method allows simultaneous determination of stiffness components in six coordinate directions (three translations, three rotations), resulting in a 6×6 stiffness matrix for the joint [6]. The accuracy of the stiffness matrix is then verified through finite element simulation by comparing the frequencies and vibrate shapes of the modal test and simulation results. The flowchart, formulas and test system are shown in Figs. 9 to 11.

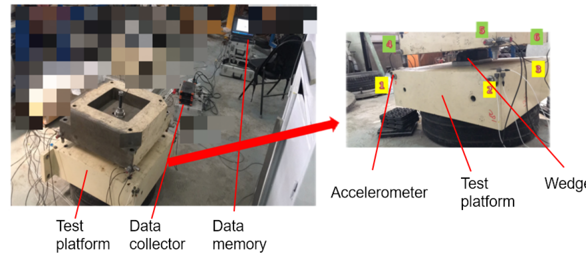
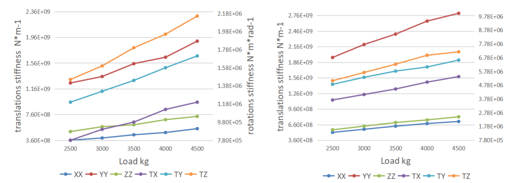
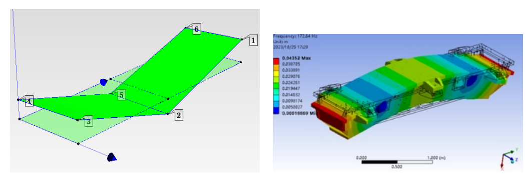


Figure 9: Test system.



(a) Girder body adjustment (b) Magnet adjustment

Figure 10: Stiffness versus load curve.



(a) measurement (b) simulation

Figure 11: Vibration shape.

Test Result

The stiffness matrices of the two adjusting mechanisms were tested separately and the results are shown in Fig. 12, where the values of the stiffness in each direction vary with the load.

Girder Body Modal Test

Girder body is a casting, and the material properties of each batch are different, so in the process of mass production, the free boundary condition modal test needs to be carried out on the girder body arriving from each batch. The results are consistent with the simulation results, as shown in Figs. 13 and 14. It fulfills the requirements of engineering use.

Motion Performance Test

Based on the installation requirements of the support unit, the motion performance test of the girder includes adjustment resolution, motion precision and locking offset [7]. As shown in Fig. 13, two dial gauges are fixed at each support points of the girder to monitor transverse (X), vertical (Y) and longitudinal (Z) offset. The dial gauges reading show that the girder can be operated by 1 µm per step in all three directions.

The motion precision of the girder is largely determined by the coupling of the motion. In the actual alignment process,

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Table 3: Plinth Measurement Data

Type	No.	Free BC frequency Hz				Grouted frequency Hz
		design	Measured mean value	Measured max value	Measured min value	Measured mean value
MP	96	≥120	144	154	135	428 Hz
FODO	96	≥150	177	187	166	452 Hz
DQ	96	≥590	629	666	599	585 Hz

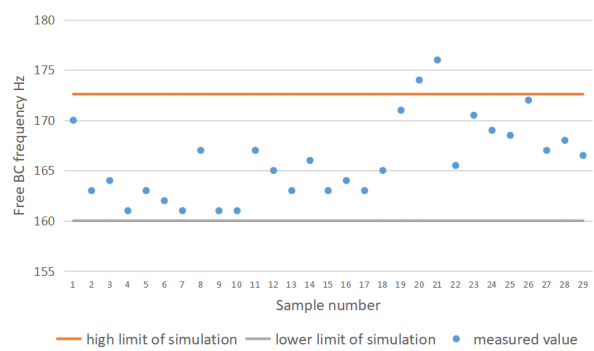

Figure 12: Free BC frequency measured value.

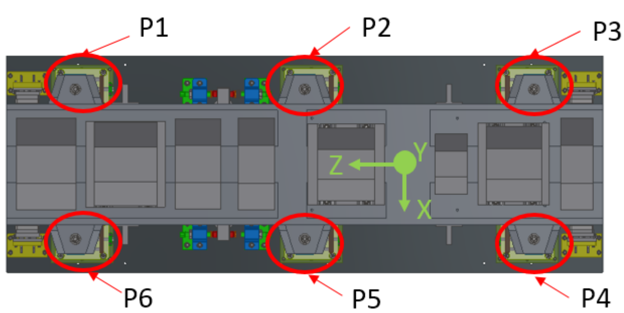

Figure 13: Schematic diagram of measuring point.

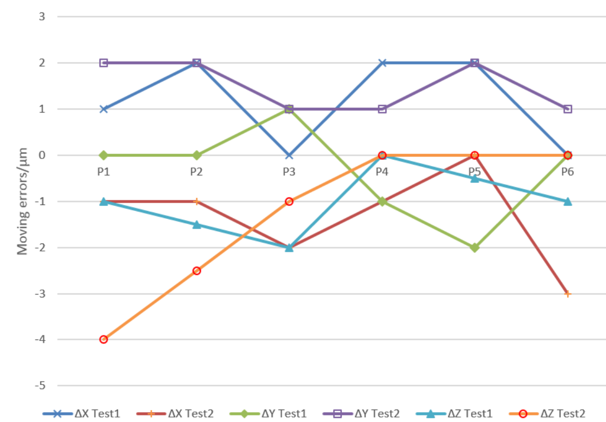

Figure 14: Motion precision test result.

the vertical position is adjusted firstly, the coupling amount can be compensated in the subsequent horizontal adjustment. Therefore, the test mainly focuses on the motion coupling in horizontal adjustment.

In the test, 20 μm was used as the motion step, and the change of the dial gauges reading is recorded. The moving precision results are shown in Fig. 14. It can be seen that the moving errors of each measurement point in 3 directions are all less than 5 μm.

The motion coupling result in horizontal adjustment is shown in Figs. 13 to 14, and the position variation is less than 3 μm.

Stability Testing

Modal testing was performed on the units after installation into the storage ring tunnel to measure their stability. Modal testing was completed for 204/288 units, results are shown in the Table 4, and the results were better than the design requirement of 54 Hz.

CONCLUSION

The requirements of HEPS storage ring magnet support are very challenging. The girder body and magnet hierarchical adjustment structure provides structural support for the realization of alignment accuracy, and high stiffness is a key concern of the structural design process. The plinth grouting experiment determines the engineering construction program of epoxy-based secondary grouting. The paired use of modal testing and simulation can obtain a more accurate value of the stiffness of the adjustment mechanism. The motion performance test results of the prototype provide a basis for the smooth implementation of the alignment process while verifying the adjustment performance of the support system. The support system test results of the tunnel show that the performance fulfill the design requirements.

Table 4: Support System Measurement Results

Typology	No. of tests	Measured mean value	Measured max value	Measured min value
MP	69	99.7 Hz	106 Hz	90 Hz
FODO	47	75.9 Hz	82 Hz	70 Hz
DQ	88	104.7 Hz	116 Hz	94 Hz

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REFERENCES

[1] HEPS preliminary design report.

[2] C. H. Li *et al.*, "Design and Progress of Mechanical Support in HEPS", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 4180–4182. doi:10.18429/JACoW-IPAC2019-THPTS034

[3] Brian Norsk Jensen, "The MAX IV stability approach – From meters of clay to nanometers of optical stability", in *2nd Swedish-German Workshop on X-Ray Optics*, Berlin, Germany, April 2015.

[4] J. T. Collins, H. Cease, S. J. Izzo, Z. Liu, J. Nudell, and C. A. Preissner, "Preliminary Design of the Magnet Support and Alignment Systems for the Aps-U Storage Ring", in *Proc. MEDSI'16*, Barcelona, Spain, Sep. 2016, pp. 87–89. doi:10.18429/JACoW-MEDSI2016-MOPE34

[5] Lei Wu *et al.*, "Design and Test of the Beam-Based Alignment Sextupole Experimental Mover Prototype for HEPS", *Radiat. Detect. Technol. Methods*, vol. 5, pp. 570–575, 2021. doi:10.1007/s41605-021-00287-0

[6] P. Becker *et al.*, "Using rigid-body dynamics to measure joint stiffness", *Mech. Syst. Signal Process.*, vol. 13, no. 5, pp. 789–801, 1999. doi:10.1006/mssp.1999.1232

[7] Chunhua Li *et al.*, "Design and test of support for HEPS magnets", *Radiat. Detect. Technol. Methods*, vol. 5, pp. 95–101, 2021. doi:10.1007/s41605-020-00223-8