Optimization analysis using orthogonal array designs for magnet girder assembly of SSRF

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Abstract An optimization analysis for finite element (FE) results by variance analysis method (VAM) of orthogonal array designs (OADs) was performed to improve the dynamic performance of the prototype magnet girder assembly (MGA) in the storage ring of the Shanghai Synchrotron Radiation Facility (SSRF). Seven factors were considered. The analyses show that the most important factor for the first eigenfrequency is stiffness of the support systems, and the main factor resulting in the relatively low first eigenfrequency of the MGA is its weak support systems. From the OADs optimization analysis, mechanical design of the MGA was improved, and its dynamic performance was improved obviously.

Key words Finite element, Optimization, Orthogonal array design, Dynamic performance

1 Introduction

Dynamic performance of the magnet girder assembly (MGA) in a storage ring affects electron beam quality significantly, which is a key issue for Shanghai Synchrotron Radiation Facility (SSRF), a third-generation light source. However, the prototype MGA of SSRF did not seem to have a good dynamic performance, because the first eigenfrequency was relatively low under the magnet weight[1]. In this paper, we focus on optimization of the prototype MGA.

In a number the third-generation light source projects[2–13], researches were carried out for different types of MGA structures, and dynamic performance of the MGAs were improved through finite element (FE) analysis. However, due to complexity of MGA, these works could hardly provide overall suggestions in the initial design stage of SSRF, especially for the structure optimization. Instead, the girder parameters, such as the plate thicknesses, and stiffness of the support systems, were mainly determined by experiences of previous design in similar projects.

Various methods were suggested for the structure optimization, such as branch and bound methods[14], a dual method[15], genetic algorithms[16], tabu search method[17], etc. However, these methods would need a tremendous number of iterations for the MGA-structure optimization. In addition, the significance of individual factors, which is important for the initial mechanical design, could hardly be identified. Therefore, optimization analysis of finite element (FE) results using ANSYS software by the variance analysis method (VAM) of orthogonal array designs (OADs) was performed. Based on an extensive survey of similar projects, seven factors, mainly thickness and position of the parts, were considered. The OADs optimization could be done by just eight FE analysis times, rather than 128 FE analysis times for the common optimization.

The main factor causing a lower first eigenfrequency in the prototype MGA was found. The dynamic performance was improved obviously by modifying the girder structures according to the optimization results by the VAM of OADs.

Supported by National Nature Science Foundation of China under Grant No.10805072

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Received date: 2011-08-23

2 Performance of the prototype MGA

Figure 1 shows the longest prototype MGA in the R&D period of SSRF. The girder had a box structure welded from steel plates in thickness of 30−50 mm, and the support system adopted the 'six-strut' structure. Results of dynamic measurements showed that the first eigenfrequency f_1 was only 5.9 Hz with the longitudinal-translation modal shape[1], which is lower than that of other light sources of the third-generations. So it was imperative to find key factors affecting dynamic performance of the MGA, so as to modify its structure in the following mechanical design.

Fig.1 The prototype MGA.

3 OADs optimization for the MGA

3.1 Schedule of FE calculation

According to design of the SSRF storage ring, the modified MGA was of a box structur**e.** Figure 2 shows a typical MGA, which was the heaviest and longest one in the cell, and had the worst dynamic performance.

The seven factors in Fig.2 were considered in two levels in the girder design and fabrication, by investigating girder structures of similar projects.

(1) Factor A, thickness of the top and bottom plates. From mechanics point of view, a box structure of thicker plates has better stiffness, which is in favor of dynamic performance of the MGA. However, an MGA can be too heavy to have a good dynamic performance. In order to understand the plate thickness effect on dynamic performance, we used two thicknesses for the plates, i.e. 30 mm in the initial design (Level 2), and 1.3 times larger than that, 40 mm (Level 1).

(2) Factor B, thickness of the side plates. This thickness affects the dynamic performance of the MGA similarly, and 30 mm in the initial design (Level 2) and 40 mm (Level 1) were used.

(3) Factor C, horizontal position of the support which was 400 mm in the initial design (Level 2), being similar to the SPEAR 3, ALS and TPS; and it was 0 (Level 1), too, just like the ESRF and APS.

(4) Factor D, vertical position of the support. It is leaned against the top plate of the girder body (Level 2), which is similar to DIAMOND, ALBA and TPS; and we changed the structure to let it align with the bottom plate (Level 1), just like the SPring-8, AS, APS and ESRF.

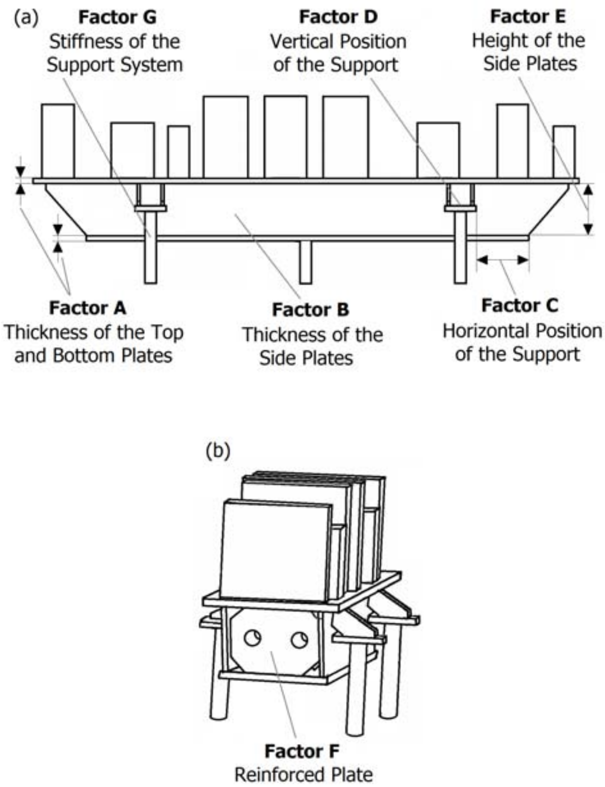

Fig.2 MGA to be optimized. (a) front view and (b) 3D profile.

(5) Factor E, height of the side plates, being 400 mm in the initial design (Level 2), which is similar to DIAMOND, AS, NSLS-II, ALBA and TPS with higher side plates; and we used a flat side plate (250

mm, Level 1) , just like the ESRF, APS and TLSh.

(6) Factor F, about the reinforced plates. Being similar to the APS, no reinforced plates was considered in the initial design (Level 2), We considered another structure (Level 1): seven reinforced plates of 20-mm thickness were welded to the girder body and distributed uniformly inside the box structure along the longitudinal direction (Fig.2b), just like DIAMOND, SPEAR 3, AS and TPS.

(7) Factor G, stiffness of the support systems. Three cylinders of Φ72 mm × 550 mm were used to support the MGA in the initial design (Level 2). The length was kept the same, while the diameter is 94 mm (Level 1), i.e 1.3 times larger than the initial design, in the same ratio as Factors A and B.

3.2 Results and discussion

The orthogonal array $L_8(2^7)$, which includes seven factors, each with two levels, and needs eight times of FE calculation, is suitable for this problem. The calculation results of the first eigen frequency f_1 are given in Table 1. The result analyses are given in Tables 2 and 3, respectively. In Table 2, for each factor, K_i (i=1,2) is sum of the f_1 with i level for that factor; S_j ($j=A$, B, …G) is sum square of the f_1 for the factor; DF_j ($j=A$, B, …G) is degree of freedom for the factor, which is the level number minus one, namely 1 in this paper; and MS_j ($j=A$, B, …G) is the ratio between the S_j and DF_j ($j=A$, B, …G). we note that a small S_j ($j=A$, B, C, E, F) in Table 2 indicates that the factor can be regarded as errors in the variance analysis[18]. So the S_{error}, DF_{error}, MS_{error} are equal to 1.36 Hz, 5, and 0.272 Hz, respectively. F_j ($j=D$, G) is the ratio between MS_j ($j=D$, G) and MS_{error}. $F_a[DF_j\ (j=D,\ G),\ DF_{error}]$ is the F-value at a confidence level of (1-a) against the DF_j ($j=D$, G) and the DF_{error} for the corresponding factor. Detailed expressions for the parameters can be found in Ref.[18]. The $F_{0.05}(1,\ DF_{error})$, namely a=0.05, is usually used for significant evaluation of the factors. The smaller the a value is, the more significant the corresponding factor becomes.

Table 1 Model results for the prototype MGA

No	A	B	C	D	E	F	G	f_1/ Hz
1	1	1	1	1	1	1	1	16.0
2	1	1	1	2	2	2	2	11.3
3	1	2	2	1	1	2	2	10.0
4	1	2	2	2	2	1	1	15.9
5	2	1	2	1	2	1	2	10.6
6	2	1	2	2	1	2	1	17.1
7	2	2	1	1	2	2	1	16.1
8	2	2	1	2	1	1	2	11.8

Table 2 Result analysis for the MGA

Factors	A	B	C	D	E	F	G
K_1	53.2	55.0	55.2	52.7	54.9	54.3	65.1
K_2	55.6	53.8	53.6	56.1	53.9	54.5	43.7
S	0.72	0.18	0.32	1.45	0.13	0.01	57.3

Table 3 Variance analysis of the calculation results

	S / Hz	DF	MS / Hz	F	A
D	1.45	1	1.45	5.37	0.1> a>0.05
G	57.3	1	57.3	212.2	a <0.05
Error	1.36	5	0.272		
Sum	60.1	7	$F_{0.1}(1, 5)$=4.06,$F_{0.05}(1, 5)$=6.61 $F_{0.01}(1, 5)$=16.26		

In Table 3, the F of Factor G, i.e. stiffness of the support systems, reaches 212.2, which is much larger than $F_{0.01}(1,5)$ of 16.26, indicating that the corresponding a is much smaller than 0.01. It means that stiffness of the support systems affects greatly the dynamic performance of the MGA. Also, we calculated the MGA without support systems of the No.4 in Table 2 (Fig.3a). The f_1 is 91 Hz with the model shape of bending around the lateral direction, much higher than the corresponding value 15.9 Hz (Table 1) for the MGA with support systems with the model shape of translating in the lateral direction (Fig.3b). This indicates further that the stiffness of the support systems has crucial influence on dynamic performance of the MGA. Therefore, the main factor resulting in the relatively lower f_1 in the MGA is its weak support systems. Therefore, how to improve stiffness of the support systems is the key to improving the MGA.

Similar analysis for the f_1 can also be performed on Factor D, and the analysis result is $0.05 \leq a \leq 0.1$. This shows that the vertical position of the support affects the f_1 to a certain extent. From the corresponding K value, we can know that the support system leaned against the top plate (Level 2) is better than aligned with the bottom plate (Level 1) of the girder body, as a decreased MGA center height is in favor of dynamic performance[19].

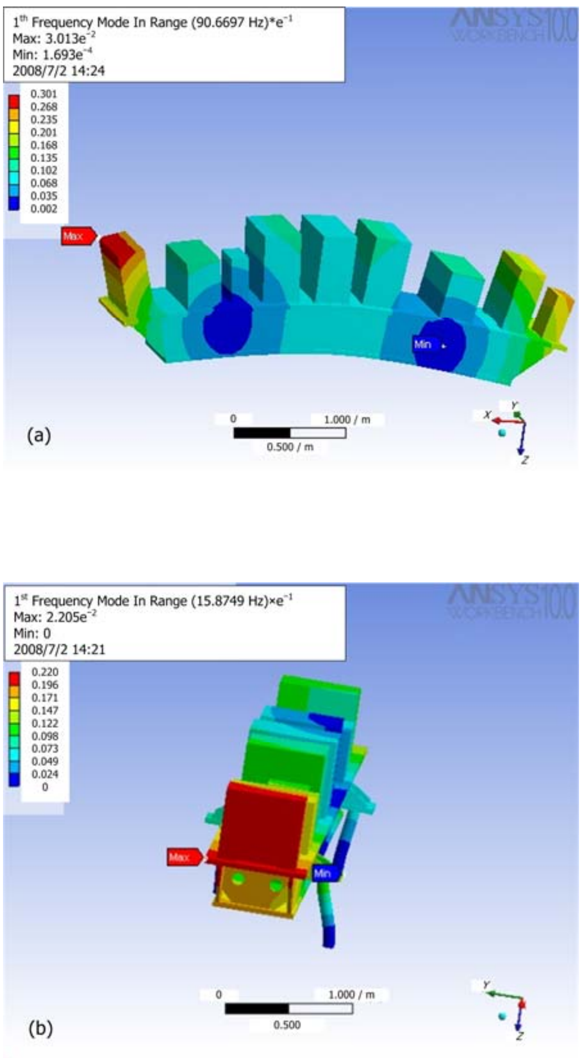

Fig.3 Results of No. 4 in Table 1 by FE analysis. (a) model shape at the f_1 without support system, (b) model shape at the f_1 with support system.

For other factors, i.e. thickness of the top and bottom plates, thickness and height of the side plates, and reinforcement of the plates, affect little on dynamic performance of the MGA within the corresponding two levels, because their S are small enough to regard them as errors in the variance analysis.

4 Dynamics of the improved MGA

Based on the above findings, we mainly made the following improvements for the girder. First, the three support cylinders were wedge in jacks instead of 'six-strut' structure. Second, to increase the f_1, three more support cylinders were added, so that each long side of the girder has three support cylinders (Fig.4a). The added steel cylinders were connected to the girder by two nuts (Fig.4b). Their bottoms were welded with a plate, and rooted in the ground by grouting material (Fig.4c). We obtained stiffness of the support systems by changing the diameters of the cylinders. Third, the vertical position of the support was leaned against the top plate.

As mentioned above, two types of the support were investigated by FE calculations and measurements. One had three support cylinders (Type A), while the other had six, with the three added support cylinders being of Φ58 mm (Type B), and the FE results are f_1=18.8 and 26.6 Hz (Table 4), respectively. From the measured transmissibility curves in Fig.4d, the f_1 is 21.9 and 27.7 Hz for Types A and B, respectively, which agree well with the FE calculation.

Figure 4e shows the FE results of Type B adopted finally by the SSRF. The model shape at the f_1 is rocked along the longitudinal direction. Dynamic performance of this MGA is obviously better than that of the R&D MGA, whose f_1 is 5.9Hz by measurement and 5.4 Hz by calculation (Table 4), indicating that the modifications improved the dynamic performances.

FE analysis showed that increasing diameter of the added support cylinders to 112 mm (Type C), the f_1 could be 33.5 Hz, i.e. an even better, stiffness of the support systems. This can also be achieved by increasing the number of added support cylinders.

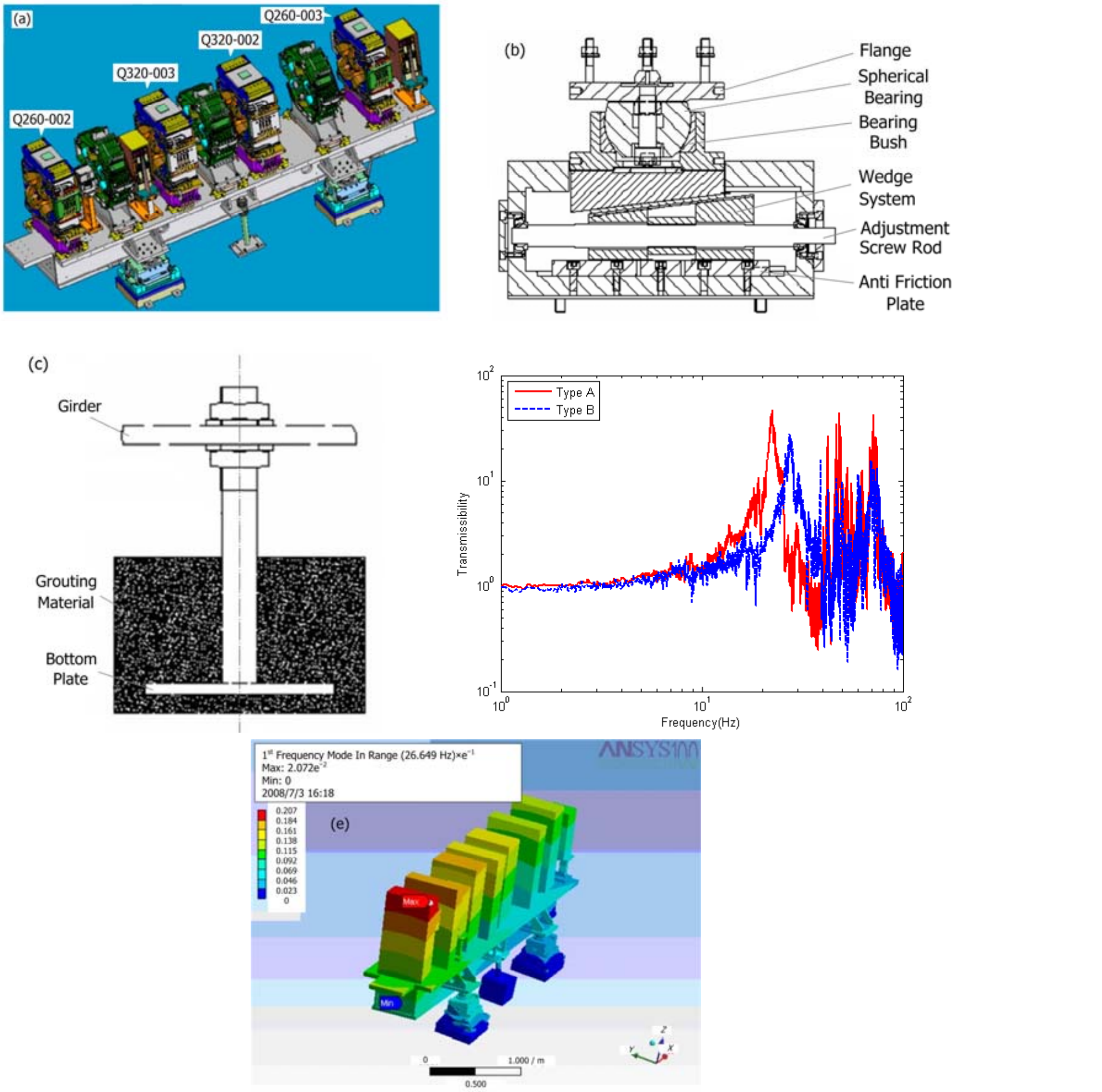

Fig.4 Dynamic performance of the modification MGA: (a) The main support system, (b) the additional support system, (c) the structure of modification MGA, (d) transmissibility curves, (e) modal shape at the f_1 for type B.

Table 4 The f_1 of the MGA.

Methods	R&D	Modified types		
		A	B	C
Measured (Hz)	5.9	21.9	27.7	—
Calculated (Hz)	5.4	18.8	26.6	33.5

5 Conclusion

In order to improve f_1 of the prototype MGA of SSRF, an optimization analysis for the FE results by the VAM of OADs was performed. Seven factors were investigated. The analysis results show that the most important factor for the first eigenfrequency is stiffness of the support systems, and next is the vertical position of the support, while the other factors have little effect on dynamic performance of the MGA. By modifying the girder structure, dynamic performance of the MGA is improved obviously.

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