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FIELD QUALITY FROM TOLERANCE ANALYSES IN TWO-HALF SEXTUPOLE MAGNET*

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Abstract

Sextupole magnets are used extensively in particle accelerators, synchrotrons, and storage rings. Good magnetic field quality is needed in these magnets, which requires machining the magnet parts to high precision and is the primary driver of the high fabrication costs. To minimize the fabrication costs, a magnetic field quality study from tolerance analyses was conducted. In this paper, finite element analysis (FEA) using OPERA was performed to identify key geometric factors that affect the magnetic field quality and identify the allowable range for these factors. Next, geometric and dimensional tolerance stack-up analyses are carried out using Teamcenter Variation Analysis to optimize the allocation of the geometric tolerances to parts and assemblies. Finally, the analysis results are compared to magnetic measurements of a R&D sextupole magnet.

INTRODUCTION

The Advanced Photon Source (APS) at Argonne National Laboratory (ANL) is upgrading the current double-bend achromat, 7-GeV, 3rd generation storage ring to a 6-GeV, 4th generation storage ring with a multi-bend-achromat lattice that provides dramatically enhanced hard x-ray brightness and coherent flux [1]. The new lattice has 40 sectors with 13 bending magnets per sector, including six reverse bends. Each sector includes 6 sextupoles of two different types. One has steel pole tips and produces nominal integrated sextupole field of up to 727 T/m, and the other contains vanadium permendur (VP) pole tips and produces nominal integrated sextuple field of up to 1315 T/m.

The allowable rms values for random multipole errors in units at 10 mm reference radius for the sextupoles (one unit is 0.01% of the main field component) are listed in Table 1. The requirement for magnet-to-magnet alignment within a module consisting of four quadrupoles and three sextupoles is 30 µm rms. The magnetic center of each magnet should be close to its mechanical center for ease of alignment using mechanical reference surfaces. Furthermore, the magnetic roll angle should be less than 0.4 mrad rms. These requirements place stringent demands on the magnet fabrication tolerances.

In order to achieve the required magnetic field quality and alignment accuracy at reasonable fabrication cost, magnetic and mechanical tolerance analyses are conducted to identify the key driving factors and their allowable limits, and to specify the proper mechanical tolerances for parts and assembly to control the driving factors within allowable limits.

Table 1: Allowable rms Values for Rrandom Fractional Multipole Errors for Sextupoles at 10 mm Radius

Harmonic	Normal (unit)	Skew (unit)
Octupole	8.9	8.9
Decapole	9.1	9.1
Dodecapole	4.5	0.9
14-pole	2.6	1.8
16-pole	0.7	0.7
18-pole	0.8	0.3

MAGNETIC TOLERANCE ANALYSES

Sextupoles for APS Upgrade are made of two solid steel yoke halves (top and bottom) with removable poles tips [2]. This study was carried out on the sextupole with VP pole tips, but the results can be applied to both magnets. For a two-piece design, since it is assembled from outside yokes inward to the pole tips, all the machining errors, including size, form, orientation, and location on mating features, contribute to the variation of the final pole tip surface locations. The machining and assembly errors that will affect the magnetic field quality include: i) pole tip surface profile errors; ii) top half offset horizontally; iii) top half offset vertically; iv) top half rotated relative to the bottom half; and v) pole tips misalignment along the mounting surfaces. Opera-2D finite element analyses are carried out to study the effect of these mechanical errors on the field quality. The geometric configuration for magnetic analyses in Opera is shown in Figure 1.

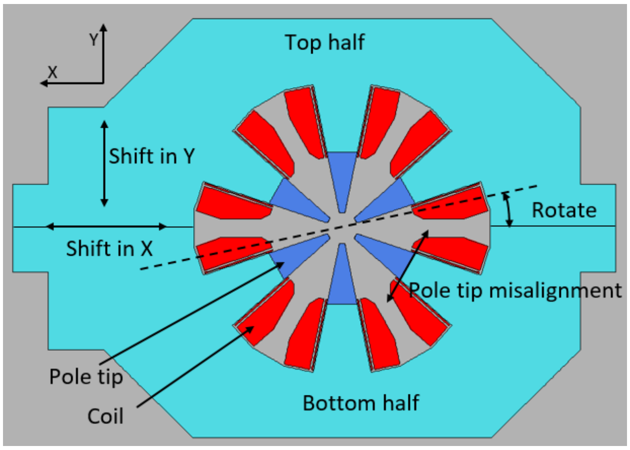

Figure 1: Configuration for magnetic analyses.

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In 2D magnetic analysis using Opera, each pole tip top region was discretized into 10 small segments. The segment vertex points on the tip surface were allowed to move normal to the surface within the profile tolerance's outer and inner boundary, as shown in Figure 2. In each case, random displacement values within the profile tolerance specifications were assigned to each vertex point. One hundred random cases were simulated using this method in order to find out the rms of multipole errors caused by the profile errors on pole tips surfaces.

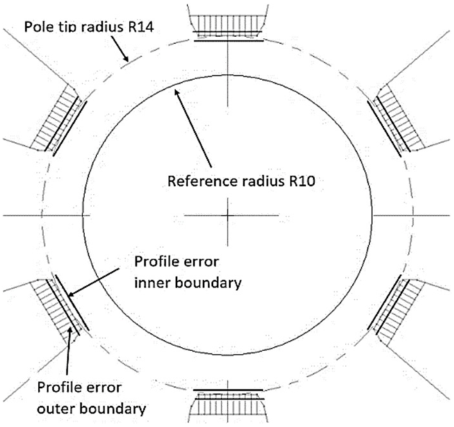

Figure 2: Sextupole pole tip configuration for profile error analyses (not to scale).

To study the effect of the top and bottom halves' shift in X direction relative to each other, the top half is deliberately shifted in the +X direction and the bottom half in the –X direction by equal amounts. Three X shift displacements, ±15 μm, ±25 μm, and ±50 μm were simulated.

To study the effect of shift in Y direction, only the top half was moved by 30 μm, 50 μm, and 100 μm since in reality, the bottom half is normally bolted down to the girder and seldomly removed. In a similar manner, to study the effect of relative rotation, only the top half is rotated relative to a stationary bottom half about the mechanical center of the magnet. Shift in Y may be caused by small debris or dust getting stuck between the mating surfaces of the top and the bottom halves. Relative rotation of the top half is generally caused by unequal tightening torques of the clamping screws or debris on one of the two mating surfaces.

Pole tips could be misaligned and displaced along their mounting surfaces and cause pole tips asymmetry around the beam. In the study, each pole tip is assigned a random displacement within the designated range to either the right or the left along its mounting surface. Four levels of displacement ranges were studied, ±25 μm, ±50 μm, ±75 μm, and ±100 μm.

MECHANICAL TOLERANCE ANALYSES

Mechanical tolerances stack-up analyses were carried out using commercial package Teamcenter Variation Analysis. In this software, parts are virtually made with the specified dimensional and geometric tolerances on geometric features. Parts are assembled and measured virtually in the same manner as they will be assembled and measured in the real world. The configuration for the mechanical tolerance stack-up analyses is shown on the right side of Figure 3. The distribution and the statistics of one of the measurement results is shown on the left side of Figure 3. The software then assigns errors within the specified tolerance range to parts using the Monte Carlo method. In our simulation, three machining tolerance levels, 12.5 μm, 25 μm and 50 μm are assigned to parts. Five thousand cases were simulated and measured for each level.

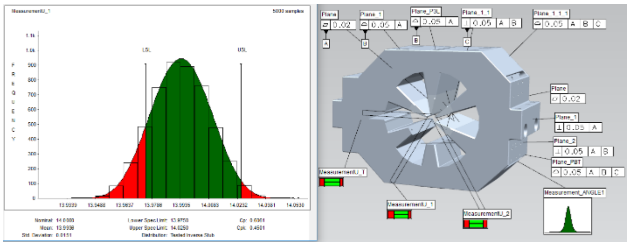

Figure 3: Configuration for mechanical tolerance stack-up analyses.

RESULTS AND DISCUSSION

The Effect of Surface Profile Error

It is found from the finite element magnetic analyses that the pole tip profile affects the rms value of all lower order random errors. The result is shown in Figure 4. In order to keep the rms random errors within specification, the profile error on pole tips must be smaller than ± 7 μm.

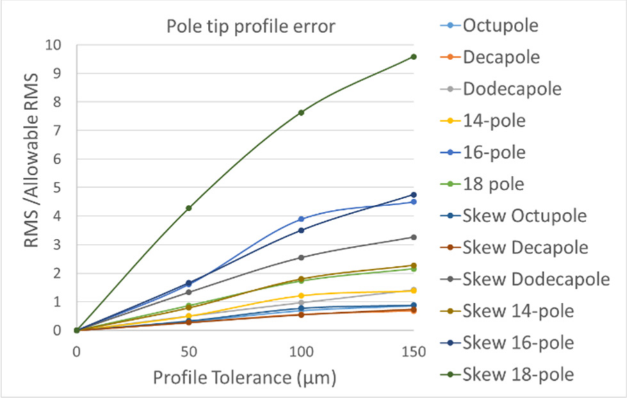

Figure 4: Effect of surface profile on the rms value of multipole errors.

From mechanical tolerance stack-up analyses, it is found that for the machining tolerance of 12.5 μm, 25 μm and 50 μm, the rms values of pole tip surfaces point variations is 5 μm , 7.4 μm and 14 μm, respectively. To keep the random errors of the magnet within spec, the machining tolerances on the pole tips need to be 25 μm or smaller. This is hard to do with conventional machining methods.

The Effect of Top and Bottom Relative Shift in X

Top and bottom relative shift in X direction affects skew sextupole, skew decapole, skew 14-pole, and skew 18-pole linearly. If the horizontal misalignment of top and bottom halves is kept below 10 μm, the largest harmonic error (octupole and above) will be 0.5 units for the skew 18-pole term which is inside 2σ of the specified rms error.

From mechanical tolerance stack-up analyses, it is found that the offset in X direction caused by machining errors on parts has a mean of 4 μm and 2 μm, and rms of 12.5 μm and 6.4 μm, at 50 μm and 25 μm machining tolerance level, respectively. This means 25 μm machining tolerance is sufficient to keep top and bottom relative offset within spec.

The Effect of Top and Bottom Relative Shift in Y

Top half offset in Y direction affects the normal decapole, and the normal 14-pole linearly. If the vertical misalignment of top and bottom halves is kept below 30 μm, normal decapole and the normal 14-pole will be kept inside 2σ of the specified rms error.

From mechanical tolerance stack-up analyses, it is found that the offset in Y direction caused by machining errors on parts has a mean of 3 μm and 3 μm, and rms of 30 μm and 16 μm, at 50 μm and 25 μm machining tolerance level, respectively. This means 25 μm machining tolerance is sufficient. However, it is critical to keep the mating surfaces clean and follow a tightening procedure to ensure even clamping of the top half to the bottom half.

The Effect of Top and Bottom Relative Rotation

Top and bottom relative rotation mainly affects the normal octupole, normal dodecapole, and skew sextupole. If the top and bottom relative rotation is kept below 0.9 mrad, normal octupole and the normal dodecapole and magnetic roll error will be kept inside 2σ of the specified rms error.

From mechanical tolerance stack-up analyses, it is found that relative rotation caused by reasonable machining errors of parts are extremely small and is negligible. However, it is critical to keep the mating surfaces clean and follow a tightening procedure to ensure even clamping of the top half to the bottom half.

The Effect of Pole Tip Misalignment

Pole tip misalignment causes both the mean and standard deviation of random harmonics to change. Figure 5 plots the ratio of multipole error rms with regard to the allowable rms value against pole tip misalignments. From Figure 5, it can be seen that if the pole tip misalignment is kept below ±10 μm, the rms value for all random errors will be below 100% of the spec.

From mechanical tolerance stack-up analyses, it is found that the pole tip misalignment caused by machining and assembly errors has rms value of 25 μm and 16 μm, at 50 μm and 25 μm machining tolerance level, respectively. This means 25 μm machining tolerance is not sufficient. More stringent machining precision is required.

Based on the magnetic and mechanical tolerance analyses, it can be seen that in order to produce magnets that meet the design requirements, high machining tolerance better than 25 μm is needed, however, it is very costly to machine parts at this precision level. Moreover, all these factors will add up to affect the overall magnetic field quality and requires a machining and assembly precision level that is not realistic. To address this issue, we have decided to use the wire EDM method for the pole tip profile at the assembled state. This way, the part level tolerances do not affect the final assembly and can be relaxed to reduce machining costs. At the same time, the pole tip surface profile, top bottom relative offset and rotation, and pole tip misalignment can all be maintained within ±10 μm. Although wire EDM is expensive, the overall cost using this method is lower than that using conventional machining method since it is limited to only the pole tip region.

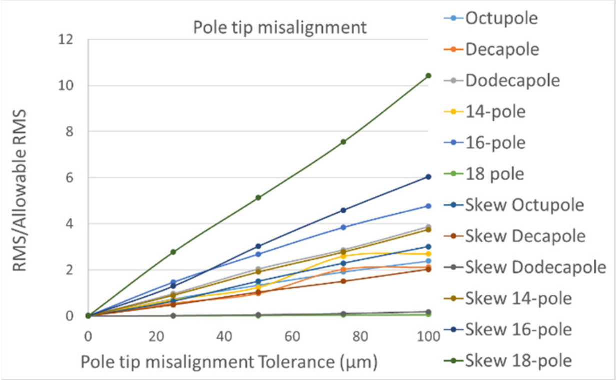

Figure 5: The effect of pole tip misalignment.

A prototype magnet with wire EDM machined VP pole tips was fabricated and measured. The measurement results of the prototype magnet matched the simulation results very well. However, we found that the hardened straight dowel pins have poor repeatability in soft magnet steels. To solve this problem, we tested taper dowel pins for yoke halves and metal filled epoxy keys for the pole tips and yokes. They can retain repeatability during reassembly within 10 μm.

CONCLUSION

Magnetic and mechanical tolerance studies were carried out for APS upgrade sextupoles. The effects of pole tip profile error, top and bottom half relative offset and rotation, and pole tip misalignment on magnet field quality in terms of random multipole errors were studied. Based on the analyses results, it is found that the conventional fabrication and assembly methods are not sufficient to achieve the tight tolerance requirements of sextupoles for APS upgrade. A new fabrication plan was developed to wire EDM the pole tips in an assembled state and to include features that ensure the repeatability of the alignment. A prototype made with this method was tested and proved satisfactory.

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