MAGNETIC FIELD INSPECTION AND ANALYSIS OF MULTIPOLE LATTICE MAGNETS USING A ROTATING-COIL SYSTEM*

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Abstract

A precise rotating-coil measurement system (RCS) was constructed to characterize the multipole errors and field centers of multipole lattice magnets in Taiwan Photon Source (TPS). The nominal tolerance of the magnet offset is designed to be within ± 0.01 mm. The quantitative accuracy of the field-center measurement of RCS is better than 0.01 mm in the horizontal and 0.02 mm in the vertical directions. The measurement reproducibility of the field center was better than 0.01 mm when the rotating-coil system was reinstalled. The relative accuracy of the multipole components is better than 2×10^{-5}. A precise 3D-coordinate-measuring machine (CMM) was used to inspect the mechanical center of magnets for comparison with the RCS results. We report the method of magnet-field-center inspection using RCS and discuss the measurement-signal transformations of the RCS.

INTRODUCTION

A novel light source is under construction in Nation Synchrotron Radiation Research Center (NSRRC), named Taiwan Photon Source (TPS). TPS is a third-generation accelerator for a light source designed to achieve high brilliance and low emittance. Highly precise magnets are therefore required to control the electron beam in the storage ring. One issue is that the centers of magnets are aligned before installation on the girder. An advanced tool to measure the magnetic field is hence important, especially for the inspection of the center of the magnet field. A rotating-coil measurement system (RCS) is a rapid and reliable tool for field measurement, used in several synchrotron radiation facilities [1-5]. A new concept and method of a RCS to measure the field center is discussed in detail in this paper.

RCS BENCH

Figures 1 display the photograph of the RCS bench. All parts of the RCS are mounted on a granite bench to fix the location [6]. The magnet was installed on a magnet base of which the structure is the same as of the girder in the storage ring. The field center of the magnet was decided by three bumps of feet, two for fixed vertical and one for fixed horizontal location. The horizontal offset of the magnet was obtained from a two-side measurement, as discussed in the next section. The height of the RCS unit is fixed by the granite support; the height of the granite support of the RCS system is machined by artificial polishing. The vertical height of the unit was measured with a dial-height gauge such that the accuracy of height can be controlled within ± 0.003 mm. The vertical offset was obtained from an average of normal- and opposite-side results. The relative resolution of the multipoles of RCS is better than 1×10^{-5}. The reproducibility of the multipoles is better than 2×10^{-5} (excluding the dipole term) when the magnet and the RCS unit undergo reinstallation. The repeatability of measurement of the magnet center is better than 0.01 mm after magnet and RCS-unit reinstallation.

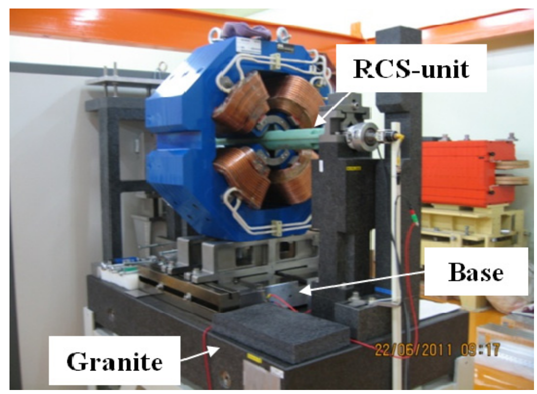

Figure 1: The photograph of RCS. The RCS-unit support and magnet base are mounted on a granite bench.

HORIZONTAL- AND VERTICAL-FIELD CENTER INSPECTION

The horizontal offset between the RCS unit and the magnet center is relative to the alignment of the magnet base. The variation of center offset between the RCS unit and magnet base will be occurred when the magnets installed by hoist and knock the base. Meanwhile, there is an unknown center offset between rotating-coil and the girder reference base. A two-sided measurement method was used to cancel the center offset between the girder reference base and the RCS unit. Figures 2 (a) and (b) display the feet of the magnet installation in the two-side measurement. The trough wall of the base was marked to distinguish normal- and opposite-side in the two-side measurement. The mark A and B are different side of magnet. The procedures of the two-sided method involve as the first step installing the magnet on the normal side of the bench and take data. The normal-side installation keeps the feet at the left side of the trough wall (Nor. side), shown in Fig. 2 (a). In the second step, the rotation of the magnet 180^{o} about the vertical axis (horizontal rotation) keeps the feet at the right side of the trough wall (Opp. side), shown in Fig. 2 (b). The normal- and

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opposite-side data will cancel the offset of the magnet base in the horizontal direction.

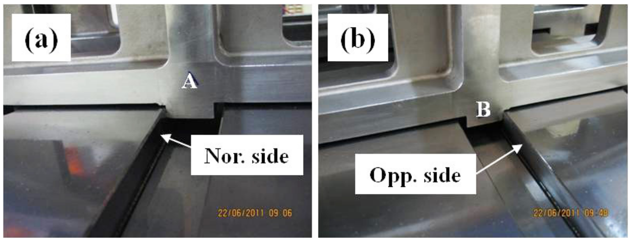

Figure 2: The feet installation of magnet in the two-side measurement. The marker A and B are the different side of magnet.

Figures 3 (a) and (b) display an exaggerated sketch of the two-side measurement of the large and small offsets. The dashed blue line marks the center of the magnet-base center. The dashed black line and red-cross mark the RCS unit and magnet center, respectively. The offset between the magnet-base center and the RCS-unit center is denoted U. The offset between the RCS-unit center and the magnet center is denoted X1 and X2 for the normal- and opposite-side measurements, respectively. The offset between the magnet-base center and the magnet center is denoted M in the measurements. Here the large offset (small offset) means an offset of the magnet-field center larger (smaller) than the RCS-unit offset, M > U (M<U). In total, eight cases will occur in an accurate measurement, four for the large offset and four for the small offset.

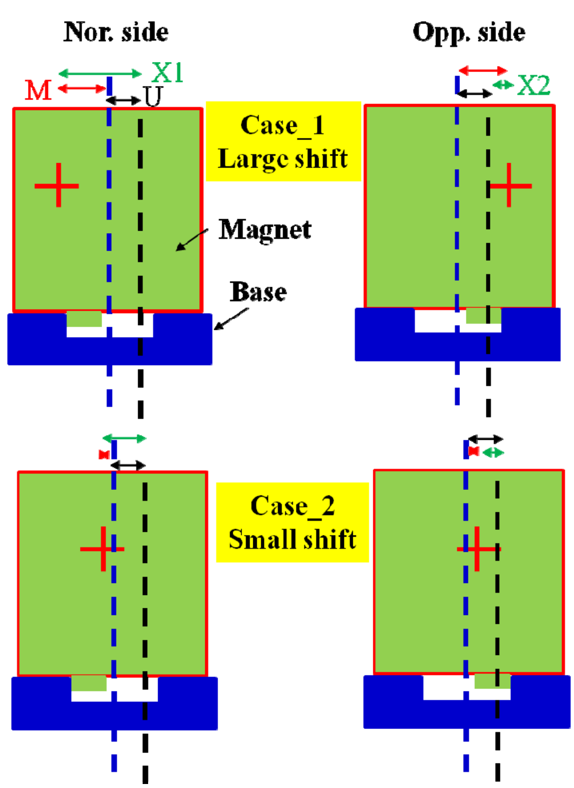

Figure 3: An exaggerated sketch of the two-side measurement of the large and small offsets.

According to the geometric position of large offset, equations (1) and (2) are obtained from normal- and opposite-side measurements; all values here are absolute lengths. Equations (1) and (2) become added to yield (3). Equation (4) is obtained from (3) because all values are positive. Equation (4) is the condition for the large-offset cases. The difference of equations (1) and (2) yields equation (5). The center offset of the large-offset cases are thus calculated from (5).

$$X1 - M = U \tag{1}$$
$$M - X2 = U \tag{2}$$
$$X1 - X2 = 2U \tag{3}$$
$$X1 + X2 > 2U \tag{4}$$
$$M = (X1 + X2)/2 \tag{5}$$

In the small-offset case, the sum of equations (6) and (7) produces (8), which means that X1 < U or X2 < U or X1 = X2 = U, because all values are positive. Equation (9) is therefore the condition for the small-offset cases. The magnet-center offset was hence calculated from equations (6) and (7) to generate equation (10).

$$X1 - M = U \tag{6}$$
$$X2 + M = U \tag{7}$$
$$X1 + X2 = 2U \tag{8}$$
$$X1 < U \text{ or } X2 < U \text{ or } X1 = X2 = U \tag{9}$$
$$M = (X1 - X2)/2 \tag{10}$$

Table 1 presents examples of the two-side measurement for Q1-P01 and Q1-P03 magnets. The offset between the magnet base and the RCS unit is 0.02 mm, obtained in a preceding measurement. The horizontal offsets of the normal and opposite sides are 0.043 mm and 0.011 mm in Q1-P01, respectively. According to equation (4), the magnet offset is 0.027 mm. After 0.02 mm horizontal shimming, the normal and opposite sides become 0.025 mm and 0.02 mm in horizontal offset, respectively. According to equation (10), the magnet offset is 0.003 mm after shimming. The difference of the horizontal offset between the cases without shimming and with 0.02 mm shimming is 0.024 mm. This result confirms the shimming thickness to be 0.02 mm. The vertical offset of Q1-P01 is 0.1 mm averaged by 0.093 mm and 0.106 mm in the two-side measurement. Similarly, Q1-P03 magnets were shimmed with 0.03 mm pieces that decrease the horizontal offset from 0.038 mm to 0.009 mm. The vertical offset of Q1-P03 is 0.005 mm.

Table 2 presents the field center and mechanical center of Q9-P01 and Q10-P01 quadrupoles measured with the CMM and RCS. The CMM results were compensated with the thermal coefficient of iron, because the temperature of the environment was different for the CMM and RCS, but the thermal effect does not influence the magnet offset in the horizontal direction. The measurement of the CMM responds only to the inaccuracy of the mechanical center. In addition, the field center of the RCS measurement was influenced by not only the feet offset but also the pole-profile error. The results of CMM and RCS therefore exhibit a slight deviation.

Table 1: Two-Side Measurement of Q1-P01 and Q1-P03

		Q1-P01		Q1-P03	
		Without shim	0.02 shim	Without shim	0.03 shim
Nor. side	Hor.	0.043	0.025	0.048	0.020
	Ver.	0.106	0.102	0.006	0.008
Opp. side	Hor.	0.011	0.020	0.028	0.002
	Ver.	0.093	0.093	0.001	0.001
Conditions		X1+X2 > 2U	X1, X2 ~ U	X1+X2 > 2U	X2 < U
Actual offset	Hor.	0.027	0.003	0.038	0.009
	Ver.	0.1	0.098	0.004	0.005
Base-unit offset, U=0.02 mm					

Table 2: Comparison of CMM and RCS

Magnet	Vertical offset (mm)		Horizontal offset (mm)	
	CMM	RCS	CMM	RCS
Q9-P01	0.042	0.067	0.030	0.011
Q10-P01	0.051	0.081	0.111	0.124

FIELD TRANSFORMATION AND CALIBRATION OF RCS

The transformation of the RCS from the integrator count (I_{VS}) to the field strength (I_{Tm}) depends on the coil number, the coil scan dimension in the field, the divider and the harmonic number; see equation (11) [7]. Table 3 shows the transformation of quadrupole and sextupole magnets in the storage and booster rings.

$$I_{Tm} = I_{VS} \times \frac{10^{2(n-2)}}{2\times N\times p\times D^{n}}\ Tm^{n-1} \qquad (11)$$

Here, I_{Tm} is the normal field strength in T/m^{n-1}. I_{VS} is the integrator signal in unit V×S, N defines the number of coil turns, p is a divider multiple, D is the rotation radius of the coil in unit cm, and n is the harmonic index number. The coil turns number 3 and the rotation radius of storage-ring magnets is 3.3 cm on the printed-circuit board (PCB). The divider multiples are 1, 2 and 4 for 1024, 512 and 256 trigger points per revolution in the 1024-count rotary-encoder, respectively. The index numbers 1 and 2 denote the quadrupole and sextupole, respectively.

Table 3: Unit Transformation of RCS

	Div.	Trig. per revolution	Index	Integrator counts	Field strength
unit	-	(pulses)	-	($\times 10^4$, V×S)	($T\ m^{n-1}$)
SR-	1	1024	1	1.0171	5.1368
QM	4	256	1	4.0683	5.1367
SR-	1	1024	2	0.3973	60.8118
SM	4	256	2	1.5903	60.8452

SUMMARY

A RCS was constructed to measure the multipoles, field strength and magnetic-center offset of magnets. The horizontal offset was calculated from the horizontal results of the two-side measurement. The vertical height of the magnet center was obtained from the vertical average of the two-side measurement. These measurement results were confirmed with a shimming test and CMM. The field strength of the RCS was obtained by a transformation formula.

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