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DEVELOPMENT OF MAGNETIC HARMONICS MEASUREMENT SYSTEM FOR SMALL APERTURE MAGNETS

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Abstract

To achieve high brightness of x-ray light source by making beam size and beam emittance smaller and enlarging the beam intensity, the accelerator magnet has been improved to have a larger magnetic field gradient and complex function with small aperture size. Traditional field measurement methods such as hall probe and rotating loop have difficulties in measuring the harmonics of a magnet with a small aperture due to restrictions of physical sizes of the hall sensor and loop-card.

We are developing a well-known harmonics measurement system that uses thin wire, Single Stretched Wire magnetic field harmonics measurement bench, for 4th generation synchrotron radiation accelerator with small aperture(under 20 mm) magnet such as Ochang, Korea.

Not circular interpolation but, by adding a rotary stage to make an actual circular path using the additional stage, we are studying to combine a rotating loop method. In this paper, we are describing the development of the SSW system and the result of the performance test by using simple Halbach quadrupole magnet array.

INTRODUCTION

Prototype Single Stretched Wire field harmonics measurement system and simple Halbach quadrupole array were tested. With 3d printed part and permanent magnet, we developed python base operation GUI program. Since we used same driver and voltage measure unit, we could directly transplant the system to more precise linear stage without modification. To get a more stable result, data post-processing was performed. Three different types of wires were used and compared. Figure 1 shows schematic of prototype SSW bench.

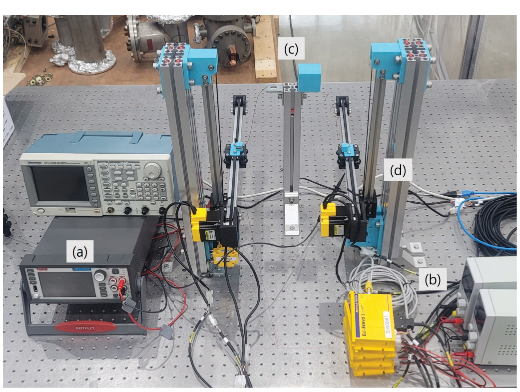

Figure 1: Schematic of Prototype SSW bench (a) Keithley 2450 (b) Driver and SMPS (c) Simple Halbach magnet array (d) 3D printed linear stage.

BASIC THEORY

At the regions where no current and no permeable materials, we could combine and express scalar potential V and vector potential A in to a one single complex representation. [1]

$$\overrightarrow{W}(x,y) = \overrightarrow{A}(x,y) + iV(x,y) \quad (1)$$

By expressing scalar potential V and vector potential A as a one single complex representation, we could derive a magnetic field from complex representation that is the solution of the homogeneous Poisson's equation, Laplace's equation.

Complex representation is a part of general solution of Laplace's equation that is an analytic function at $z = x + iy$. Let 2D magnetic field $\overrightarrow{B} = Bx + iBy$, then a complex conjugate of B, B* is given; [2]

$$\overrightarrow{B^*} = i\frac{d\overrightarrow{W}(z)}{dz} = i\left(\frac{\partial\overrightarrow{W}}{\partial x}\frac{dx}{dz} + \frac{\partial\overrightarrow{W}}{\partial y}\frac{dy}{dz}\right)$$
$$= i\left(\frac{\partial\overrightarrow{W}}{\partial x} + \frac{1}{i}\frac{\partial\overrightarrow{W}}{\partial y}\right) = \frac{\partial\overrightarrow{W}}{\partial y} + i\frac{\partial\overrightarrow{W}}{\partial x}$$

$$\text{Thus, we could get } B_x = \frac{\partial\overrightarrow{W}}{\partial y}, B_y = -\frac{\partial\overrightarrow{W}}{\partial x}$$

Let multiply C_n, a complex constant, to $z^n = (x+iy)^n$. Because of all the complex variable function always satisfy the Laplace's equation, $C_n(z)^n$ also satisfy the Laplace's equation. When the scalar potential and vector potential are constant values, Eq. (1) shows curves that can be expressed with $C_n(z)^n$. Also, real part of $W(z)$, vector potential $\vec{A}$ and imaginary par of $W(z)$, scalar potential V are orthogonal. So, we could get each other values by following the other one. This explains the induced voltages when measured by a wire that moves at the constant B field are perpendicular components of the moving wire path.

Measured integral voltage V and B field has a relation below [3].

$$V = \frac{d\Phi}{dt}$$
$$\phi = \text{total flux between wire movement}$$
$$\Phi = L_{eff}\int B(s)ds$$
$$\frac{d\Phi}{dt} = \frac{d\Phi}{ds}\frac{ds}{dt} = L_{eff}B(s)\frac{ds}{dt}$$
$$\therefore V = \frac{d\phi}{dt} = L_{eff}B(s)\frac{ds}{dt}$$

Wire moves at constant velocity and $L_{eff}$is constant at the same magnet. So, with constant coefficient C, we could set $B = C \times V$.

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Discrete Fourier transform with order of n, number of measurements N, was used to calculate the harmonics of the magnet array [4, 5].

$$A_n(r_0) \approx \frac{2}{N}\sum_{k=0}^{N-1} B_r(r_0,\varphi_k)cosn\varphi_k,$$

$$B_n(r_0) \approx \frac{2}{N}\sum_{k=0}^{N-1} B_r(r_0,\varphi_k)sinn\varphi_k$$

INSTRUMENT AND METHODS

Using the 3D printed components and timing belts, we build a pair of linear XY stages and measure the Halbach quadrupole array with 1T NdFeB permanent magnets. Keithley Source Measure Unit 2450 and EZ servo motor and driver were used for measuring the induced voltage signal and motorizing the stage. When the wire reached the predefined target position, InPos flag was set, and the trigger I/O signal was sent to the Keithley 2450. But the trigger signal and the measurement were not equally time spread. Since the measurement was not equally time spaced, we increase the turn number up to 100 times to reduce the spacing error. All the measured voltage was stored in the Keithley 2450 internal memory buffer and returned when the measurement is over. We applied a moving average filter to reduce the noise error level. Number of counting that is averaged were set to 10 considering a trade-off between speed and noise error. 0.1ϕ, 1ϕ enamel coated wire and 1ϕ BeCu wire were used. Unlike the other wires 1ϕ BeCu wire didn't have to peel off the surface and easily soldering to voltage measure unit. Figure 2 shows simple Halbach quadrupole magnet array has been analyzed by OPERA 3D. Build-in BH curve of the 1T NdFeB was used and 3D printed parts were not concerned. Figure 3 shows B field along the wire.

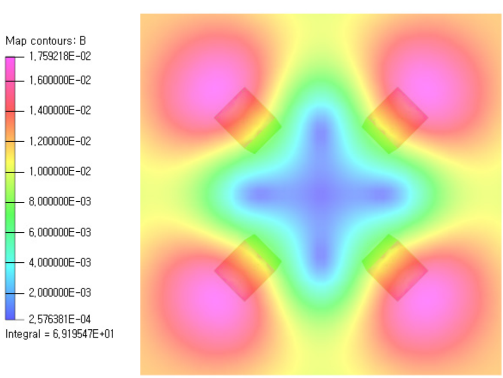

Figure 2: The magnetic field distribution of the Halbach quadrupole array.

POST PROCESSING

Before the result analysis, we set the range of measurement that the speed of the wire reaches a constant value. The wire accelerates 0 to 1000 user unit which is one turn per 1sec of spur gear. Also, the wire decelerates 1000 to 0 at the end of the measure. We exclude the first and the last turn due to the above acceleration and deceleration section by using the polarity and inflection point. Considering the direction of a Keithley 2450 probe and B field, we could determine the polarity of the magnet. At some points that the polarity has changed, we set those points as inflection points. Since the Halbach quadrupole has 4 poles, every 4 inflection points mean 1 turn of rotation. The rotation of the wire starts at the 45 degree position of the Halbach array, so we compensate for an initial value.

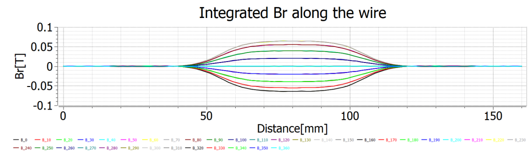

Figure 3: Integrated Br field along the longitudinal direction.

RESULT ANALYSIS

Figure 4 shows 10 turn CCW direction measurement split into 1 turn(2π) by using the polarity and inflection point. Every extreme points represent the closed points to the pole tip. Since the wire accelerate to constant speed and decelerate to stop, the first and the last turn are much more unstable than others.

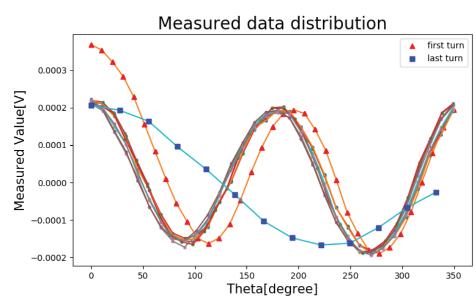

Figure 4: Data point distribution divided into 2π.

Two result that analysis same measurements are compared at Fig. 5. We visualize the measured voltage, strength and direction of a vector, and the coefficient of each order.

Figure 5a shows raw data analysis that no cut off and with no compensation. Since there is no first start point compensation, B field and positions are not matching at all. When we compensate initial value, 1st quadrant Z section graph is matched with real Halbach magnet array. Measured values that multiplied to calculate the harmonics are much affecting to harmonics then error form theta spacing. When we exclude the first and last turn, 2nd order coefficient increased. Post processed data analysis result Fig. 5b shows this well. The main multipole components of quadrupole, 2nd order, a coefficient of 2nd order were bigger then other about 100 times. The average calculated harmonics of clockwise 10 turn was 1.14^{-2}.

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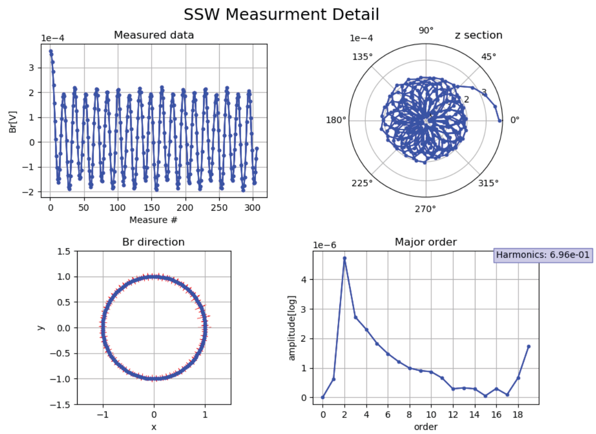
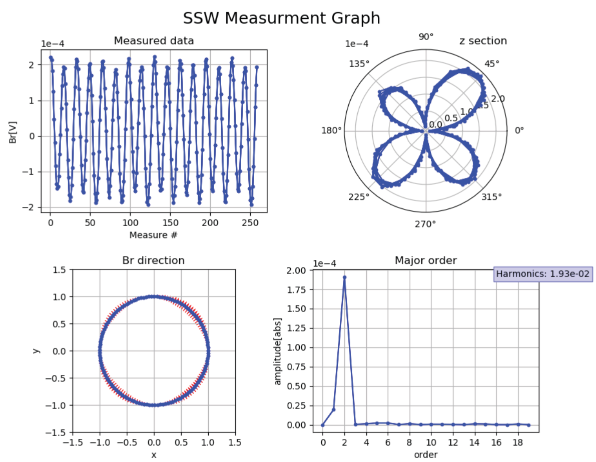


(a) Before post processing.



(b) After post processing.

Figure 5: Post processing comparison.

SUMMARY AND PLAN

We realize that the 2nd quadrant pole is weaker than the others and at the same time, the 1st quadrant is stronger than the other. To imitate the result at OPERA 3D, we change the magnet strength, off-axis wire, sagging of the wire, and precession of wire. None of that changes imitate the non linear error of measurement result. Figure 6 shows how to mimic the wire sagging at OPERA 3D. Figure 7 shows the result of 10 turn measurement with sagging wire.

Since the linear stage circular interpolation motion is not actual circle, but smooth zigzag motion, we are going to add a rotary stage on the both linear stage. By adding a rotary disk and stage, this bench able to use rotating loop method for measuring harmonics. Magnet bore that frequently used will be measured by the PLC printed rotation loop or pair of wire and specially small, two or more magnets at same girder will be measured simultaneously by SSW.

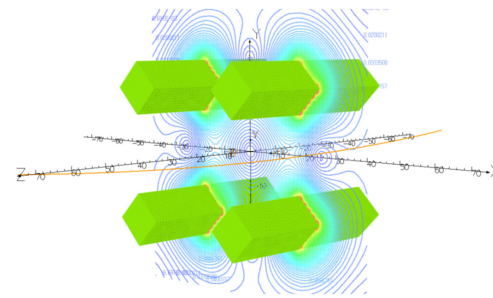
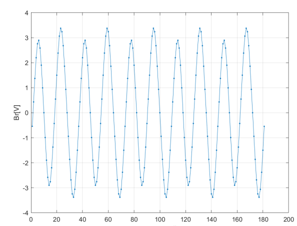
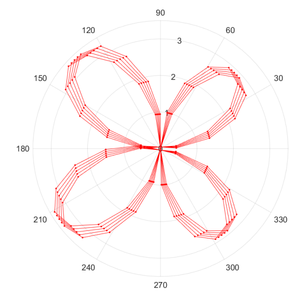


Figure 6: Wire sagging simulation at OPERA 3D.



(a) Measured Br[V]



(b) Z section field distribution

Figure 7: OPERA 3D error simulation.

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