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Rotating/Helmholtz coil system using a lock-in amplifier method

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Measurement of integrated magnetic induction is an important part of the construction of insertion devices. The so-called ‘flipping coil system’ is normally utilized to characterize the integrated multipole components of the device, a requirement which varies from one storage ring to another. A Helmholtz coil system is used to determine a magnetization vector of each magnet piece in the device. Both systems are designed to measure the integrated magnetic flux to deduce the necessary quantities using the known relationship. We have developed an unconventional system which has a continuously rotating mechanism that allows the use of a lock-in amplifier instead of an integrator or a voltmeter. Detailed descriptions of the equipment are given.

Keywords: insertion devices; integral multipoles; magnetic measurement.

1. Introduction

The importance of accurate magnetic measurement in the construction of accelerators and insertion devices (IDs) is now emphasized more than ever because of stricter tolerances on the field quality required by modern machines. In particular, the field integral measurement of insertion devices requires more sensitivity than those of lattice magnets of an accelerator. In this paper two types of magnetic measurement systems, each utilizing a lock-in amplifier, are described. In §2 a rotating coil system is described, which is used to measure the integrated multipole components of a minipole undulator called IVUN and some SPring-8 IDs (see *Insertion Device Handbook*, 1996). §3 deals with a coil system that determines the magnetization vector of each magnet piece in an ID. Some measurement results obtained with these systems are presented in §4.

2. Rotating coil system

Conventional flipping coil systems (Chavanne, 1989) employ multi-turn coils whose output is passed to an integrator or a programmable voltmeter for integration. The coil usually has a limited rotation-angle range within which the integration must be performed. As a consequence, all the frequency components of the output voltage from the coil must be included and noise filtration becomes a major obstacle. It is known that one of the most effective means of noise reduction is to limit the bandwidth of the measurement. In order to apply this type of method (which is in practice realised by the use of a lock-in amplifier) to a flipping coil system, one needs a connector that enables the rotation of the coil while maintaining electrical contact. A rotary connector (Model 205) fulfills this condition by having mercury as an interface medium. Another advantage of using a lock-in amplifier is that both normal and skew components of the first integral can be measured simultaneously as the two quadrates. The first integral Ii and I_x can be derived from the following equation,

$$V = Nd\omega(Ii \sin \omega t + I_x \cos \omega t) = A \cos(\omega t - \varphi), \qquad (1)$$

where V is the induced voltage from the coil, N is the number of coil turns, d is the coil width and ω is the angular frequency of the rotation. The lock-in amplifier measures A and φ. The second integral θ_x can be calculated using a coil with one side rotated by 180° as follows (Frachon *et al.*, 1995),

$$\theta_x = -\varphi_x/\Theta + LI_x, \qquad (2)$$

where $\Theta = d/L$, L is a half-length of the coil and φ_x is the coefficient of the sin component of the integrated flux. The same expression applies to the y component by changing the subscript from x to y.

Fig. 1 is a semi-schematic representation of the system layout. Two stepping motors (Oriental Motor UPK-569-NAC) rotate the coil at a rate of 5 Hz. The motor controller (Tsuji Denshi flip-coil controller) ensures synchronization of movement of the two motors to less than 0.1°. The absolute rotary encoder (K+R CE-65-P) has 3600 divisions per turn, while the minimum motor step is 0.1°. The multi-turn coil is made of Teflon-coated tungsten wire (Nippon Tungsten) of 0.1 mm diameter. The coil width is 1.5 mm with four turns and the length is 1.6 m. Copper wire was deemed to be inappropriate as rather high tension (1 kgf per wire; 1 kgf = 9.81 N) is required to maintain a constant coil width during rotation at five turns per second. In initial work with 0.2 mm diameter enamel-coated copper wire we observed a steady increase in the output voltage during the measurement due to elongation of the coil. A lock-in amplifier (Stanford Research SR850) with a digital signal processor has the advantage of having a very low detectable frequency (1 mHz). It also has a very high dynamic reserve compared to a conventional analog amplifier so that the use of an electrical noise filter could be avoided.

3. Helmholtz coil system

Like the rotating coil system, our Helmholtz coil scheme employs a lock-in amplifier in order to improve the signal-to-noise ratio. It uses an inverter motor (Sumitomo Heavy Industry, CNHM02-4085-AV-6) instead of a stepping motor since the synchronization

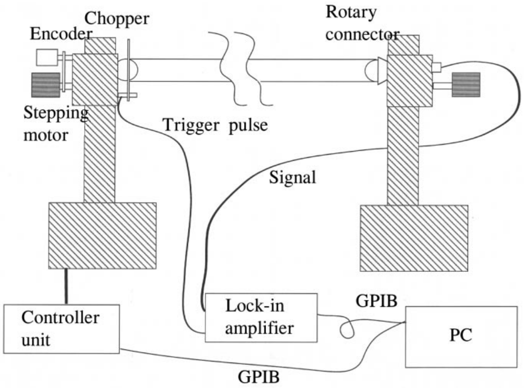


Figure 1
Semi-schematic representation of the SPring-8 rotating coil system.

of multiple motors was unnecessary. The encoder unit (Nikon RNJ10800) was chosen to ensure 0.1° resolution. However, unlike the rotating coil, this system also has, as an alternative, a conventional integrator method. The reason for this duality is as follows. Unlike integrated multipole measurement of an ID, one could expect a reasonably large signal under certain circumstances, for instance, with a large magnet block. In addition, rotation symmetry is not always guaranteed. If not symmetric, high-speed rotation generates vibration which results in extra noise. Measurement data are taken through a GPIB interface to a PC running software written in Microsoft C. A photograph of the system is shown in Fig. 2.

4. Measurement

4.1. *Rotating coil*

The amplitude and phase of nine consecutive rotating coil measurements on a SPring-8 ID (ID09) with different gap values have been recorded. The errors in terms of standard deviations are almost negligible except at one gap value (13.8 mm). As both the amplitude and the phase have higher standard deviations than other points, the electric circuit of the amplifier appears to be less stable with this particular input value. The reason for this instability is not yet understood and is currently under investigation. The average values of the standard deviation divided by its mean including this point are 0.43% for the amplitude and 0.54% for the phase. The r.m.s. value of the amplitude fluctuation is 0.67 μV and that of the phase is 0.46°, which translates to less than 1 G cm overall. Long-term drift of the zero phase of the lock-in amplifier has been observed. Therefore, a standard magnet with known field structure is used to reset the zero phase of the amplifier before the measurements start.

It is difficult to determine the absolute accuracy of this type of measurement directly. A field integral measurement by Hall probe, after careful calibration and temperature control, can barely achieve an accuracy of 10–20 G cm when the number of points in the measurement exceeds several thousand. A nuclear magnetic resonance (NMR) probe is suitable only for homogeneous fields. Variation of the earth's magnetic field in different locations can easily add up to the order of a few G cm when the device is 4.5 m long. During commissioning of the first SPring-8 device, we conducted a series of measurements to set the value of the electric current for the steering coil (ST) magnet to cancel out the kick created by the ID. Fig. 3(*a*) shows the ST magnet current with varying gaps necessary to make the orbit stay at the same position, and the measurement results of the gap dependence of the first field integral are delineated in Fig. 3(*b*). The filled squares indicate the values of the dipole kicks by the ID calculated from the observation of the closed-orbit distortion (COD). The increasing discrepancy has yet to be explained, but these COD data surely indicate the absolute level of the integral. Judging from the similarities of the curves in Figs. 3(*a*) and 3(*b*), we suspect that this discrepancy is derived from larger errors from the beam position monitor (BPM) for the electron beam further off-axis.

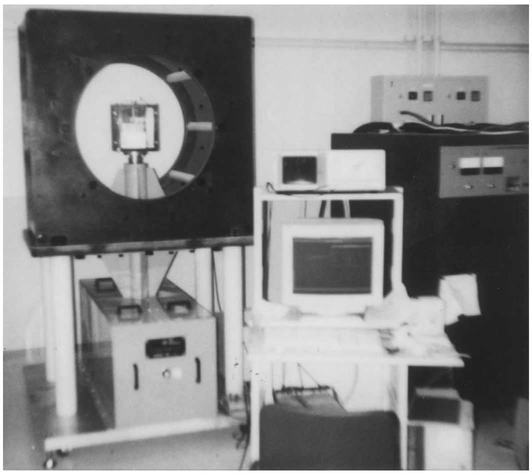
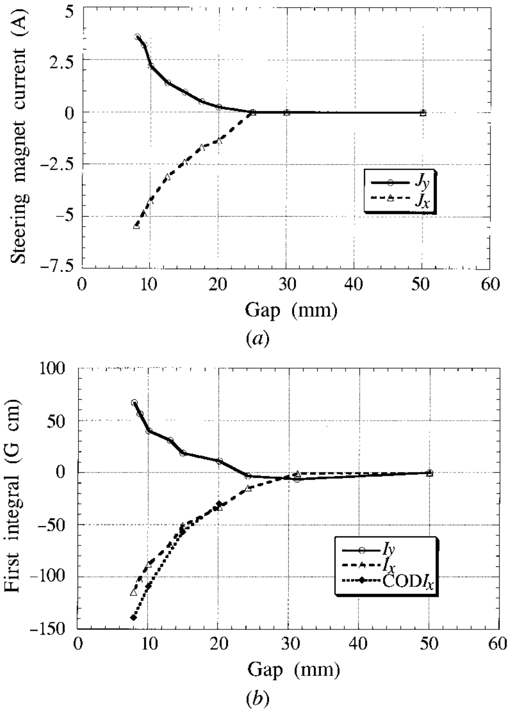


Figure 2
Photograph of the SPring-8 Helmholz coil system.

4.2. *Helmholtz coil*

First, we examined the reproducibility and fluctuation of the data by measuring the magnetization vectors of the magnets [46 mm (W) × 12 mm (H) × 8 mm (D)] used for standard SPring-8 in-vacuum undulators. Fig. 4 shows the value of the angle from the amplifier with different time constants (TCs) for a single piece. The solid line indicates the average value of 30 measurements and the broken line the fluctuations of each measurement. It can be said that even with small blocks the variation of the average value is only ±0.05° regardless of the TC settings. However, the fluctuation of consecutive measurements decreases as the TC increases. It is recommended to set the TC longer than 3 s so that a single measurement suffices the condition of 0.1° resolution.

Secondly, the accuracy of the absolute value of the magnetization angle is sought by comparing the data from this device with those recorded with a vector meter (Touei Kogyo, Inc.) used by SSMC. Fig. 5 shows the r.m.s. difference of θ measured by the



(*a*)

(*b*)

Figure 3
(*a*) Steering magnet current *versus* ID gap. (*b*) Measured first integral *versus* ID gap. Filled squares are calculated values from RF BPM readings.

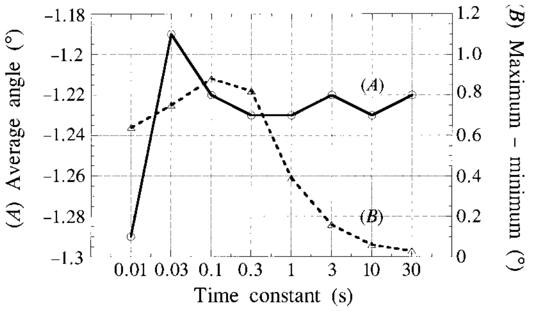


Figure 4
Average value of the lock-in angle reading (solid line) and the difference between the maximum and the minimum with the difference time constant (dashed line).

two different methods. The Helmholtz data (magnet number 12) seem to deviate statistically from the rest of data; this seems to be caused by mispositioning of the magnet due to poor machining. Ignoring number 12, the average θ difference for vertically magnetized blocks is 0.041° with a standard deviation of 0.036; that for horizontally magnetized blocks is 0.046° with a standard deviation of 0.024.

5. Conclusions

With a continuously rotating mechanism, rotating coil/Helmholtz coil systems using a lock-in amplifier have been developed. The rotating coil system has achieved a reproducibility of less than 1 G cm. The Helmholtz coil system can measure the angle that represents the deviation from the intended direction with 0.1° accuracy. Compared to conventional methods, our method is more sensitive, and less vulnerable to unwanted noise. It is particularly suitable for integrated multipole measurement of minipole insertion devices, the signal from which is inherently small.

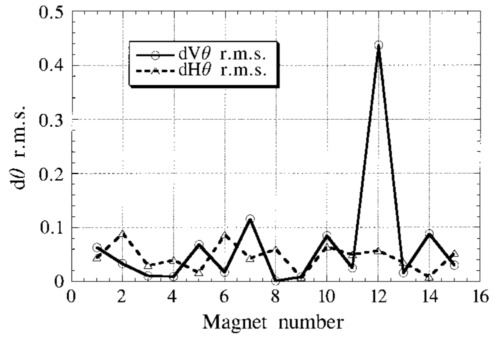


Figure 5
The r.m.s. difference between the vector meter readings and those of the Helmholz coil system. The solid line is for vertically magnetized magnets and the dashed line is for horizontally magnetized ones.

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