DYNAMIC FIELD MEASUREMENT USING A HARMONIC COIL

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Abstract

Dynamic field measurement system using a harmonic coil has been developed for J-Parc 3-GeV synchrotron magnets. For investigation of beam motion in the synchrotron, it is important to know multipole components of the actual guiding field. This system realizes the measurement of time-dependent multipole fields induced by current with the actual excitation pattern for the synchrotron magnet. This paper describes the principle of the field measurement and some remarks.

INTRODUCTION

For investigation of beam motion in a synchrotron, it is important to know multipole components of the guiding field. Usually, multipole fields are derived from the results obtained by mapping measurement (mapping method). Alternatively, they are directly measured using a harmonic coil (harmonic method). In the mapping method, correction of systematic errors due to current drift and thermal deformation of the magnet core are crucial for precise field mapping, since the measurement spends a long time. Unfortunately, such a correction is very difficult. On the other hand, the harmonic method can be performed in a short time. Therefore, the systematic errors mentioned above are not needed to be considered. In addition, such a measurement is robust against random error, since a signal from the harmonic coil is integrated by two times in order to obtain harmonic components.

As described above, the harmonic method has many advantages in comparison with the mapping method. However, the harmonic method has been performed only for a static field or the field with excitation pattern like a step. These excitation patterns are not the actual pattern for excitation of the synchrotron magnet. Furthermore, time-varying field induces eddy currents in magnet components and other neighbouring components of the synchrotron. Therefore, the actual field induced by a synchrotron magnet is superposition of a design field and eddy field. Especially, contribution of the eddy field becomes large in a magnet for a rapid-cycling synchrotron, e. g. the J-Parc 3-GeV synchrotron magnet is excited with a repetition of 25 Hz. Hence, it is essential to excite such a magnet with the actual excitation pattern in the measurement of multipole fields. For this purpose, dynamic field measurement system using a harmonic coil has been developed and applied to the measurements of time-dependent multipole fields of quadrupole magnets and sextupole magnets. Using the results of the quadrupole measurements, time-dependent tracking error is now being estimated. In the case of the sextupole measurement, the results are found to be in good agreement with the calculation using Elektra[1].

PRINCIPLE OF THE DYNAMIC FIELD MEASUREMENT

Conditions To Assure The Measurement

In this system, time dependence of the multipole filed is estimated on the basis of a sampling method. Therefore, the following conditions are necessary to assure reliability of the sampled data:

- Repetition and field strength are kept to be sufficiently stable.
- Rotational speed of the harmonic coil is sufficiently slower than the field repetition.
- There is no noise synchronizing with the coil rotation.

The first is the most important condition to assure reliability of the sampling procedure. It requires a power supply to be stable. The power supply designed for the synchrotron will satisfy this condition. The second determines the angle resolution. This condition requires large memory size for signal storage in the measurement system. The last condition relates a precision of higher multipoles. Such a noise may induce a fake multipole. Therefore, the results of a measurement must be examined under this condition.

Principle And Method Of Analysis

Fig. 1 shows a harmonic coil inserted in a quadrupole magnet for the J-Parc 3-GeV synchrotron.

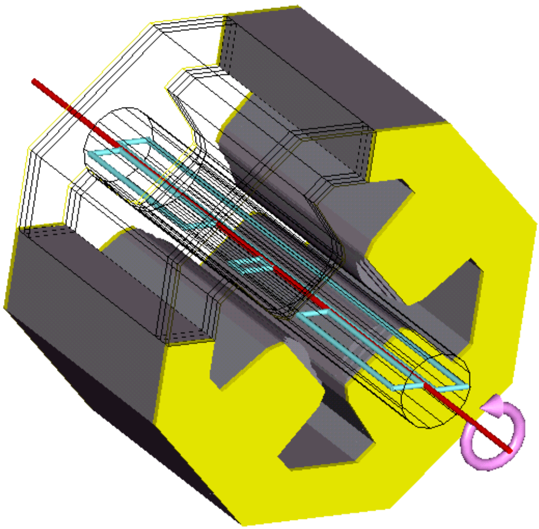

Fig. 1. Harmonic coil inserted in a quadrupole magnet.

Here, four coils are shown by the blue color. The longest coil is used for GL measurement, and the smallest coil is for the central field measurement. The coil rotates around the red axis. Rotational angle is measured by an angle encoder, which gerenrates pulses with a rate of 18,000 pulses/rotation.

A signal of the harmonic coil and pulses from the angle encoder are schematically shown in Fig. 2. These signals are simultaneously recorded in a waveform dizitizer. Then, the coil signal is integrated to obtain a flux, and the encoder pulse is counted to obtain a coil instantaneous angle, as shown in Fig. 3. In the figure, the sinusoidal field pattern is shown by the blue line.

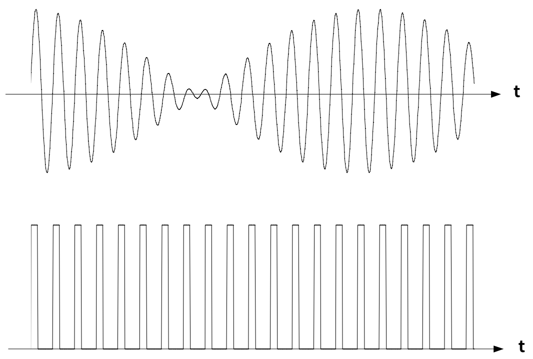

Fig. 2. Harmonic coil signal and pulses from the angle encoder.

Integrated signal, or flux, and coil angle are sampled at the definite timing in each period of the field repetition. The angle dependence of the flux at the definite timing is thus obtained.

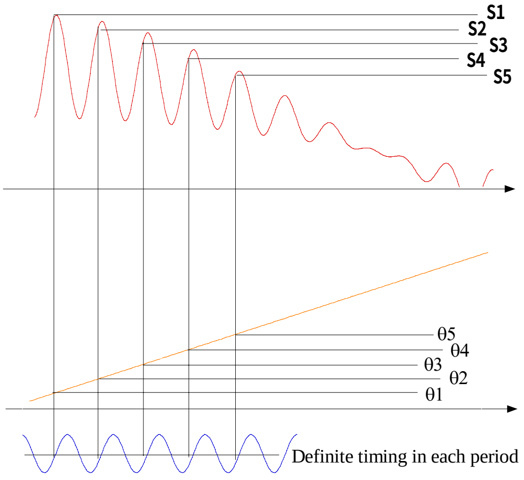

Fig. 3. Time dependence of the integrated coil signal (flux) and coil angle. They are sampled at the definite timing in each period.

The sampled data is schematically shown in Fig. 4. Sampled data must be prepared at least up to the angle of 2 π. In the figure, only the first five points are shown by a solid circle and remaining points are omitted. Then, Fourier transformation of this sampled data gives multipole fields at this timing.

By slightly changing the definite timing, another sampled data is obtained. If the definite timing is scanned within one period, time dependence of the multipole fields in one period can be obtained.

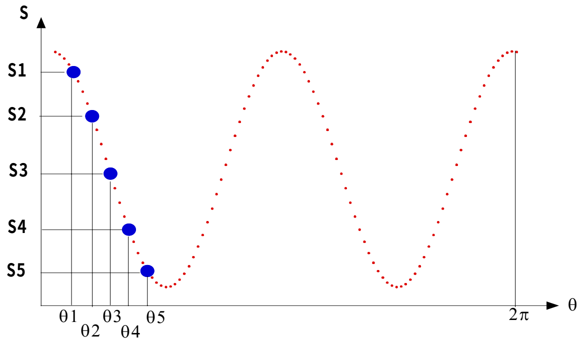

Fig. 4. Angle dependence of the flux at the definite timing.

Measurement System

The measurement system comprises a waveform dizitizer for signal storage and a controller of the harmonic coil. In the J-Parc, analog to digital converter with sampling rate of 20 kHz is used as the waveform dizitizer. Minimal signals for multipole field measurement are listed below:

- Harmonic coil signal.
- Angle-encoded signals.
- A signal for determination of the field repetition.

Here, two angle-encoded signals are needed; one is for determination of the angle origin and the other is for measurement of the instantaneous coil angle. In order to determine the field repetition, a coil placed inside the magnet gap is usually used. A start signal of the current pattern for power supply control may be also used. However, it must be noted that this timing may walk around the field timing. It is an example case that a power supply is controlled as a voltage source.

SIMULATION

In order to test a reliability of this method for estimation of multipole fields, a known field is numerically generated and analysed. If a magnet is excited by dc-biased current with sinusoidal waveform, the m-th multipole field induces the following voltage in a harmonic coil with unit width and unit length:

$$V_m = (\phi_m)_{dc}(\alpha\omega \sin\omega(t+\Delta t)\cdot\cos m\Omega t + \\ m\Omega(1+\alpha\cos\omega(t+\Delta t))\cdot\sin m\Omega t) .$$

Here, $(\phi_m)_{dc}$ is the dc component of the amplitude of the m-th harmonic field (flux) across the harmonic coil, and ω and Ω are angle frequencies of the field repetition and the coil rotation, respectively. α is the ratio of ac-amplitude to the dc-bias field. Giving a pure quadrupole, the simulation was performed. Input parameters are listed below:

- $(\phi_2)_{dc}$ =1.0, α=0.7 and Δt=0.
- Ω=2πx1/6 Hz and ω=2πx25 Hz.
- Duration of measurement=12 sec (period of two rotations).
- Sampling frequency=20 kHz/S.

Fig. 5 shows the generated coil signal up to 1 sec. Similar waveform as in Fig. 2 is obtained.

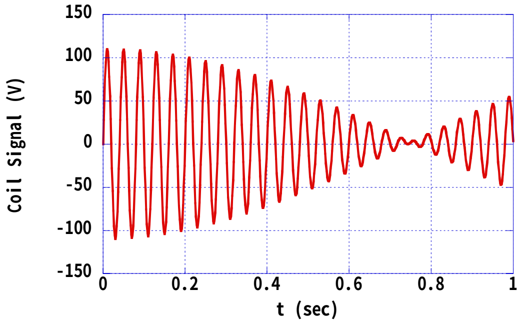

Fig. 5. Generated coil signal up to 1 sec.

After the coil signal is integrated and the coil angle is decoded, both the flux and angle are sampled at 32 timings within the period of repetition. Eight samples during the first half period are shown in Fig. 6. As shown, sampling procedure is well done.

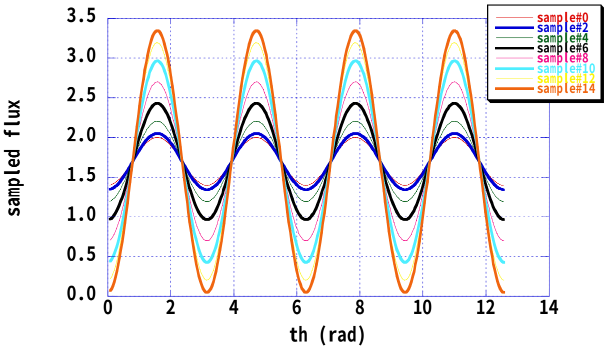

Fig. 6. Angle dependence of the sampled data during the first half period.

Fourier transformation of each sampled data is performed. The results are shown in Fig. 7. Upper figure shows the time dependence of the quadrupole component (m=2). The lower shows the time dependence of the multipoles, normalized by the quadrupole, from m=3 to m=10. The result of the quadrupole component reconstructs the expected waveform. On the other hand, the values of higher multipoles are sufficiently small, but those waveform are somehow curious. Since, as shwon in Fig. 8, such waveforms become rather smooth by changing a sampling frequency to 30 kHz/S, their behaviours seem to depend on the sampling frequency.

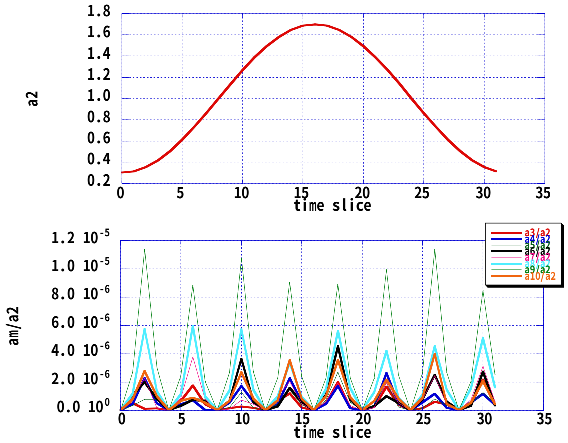

Fig. 7. Time dependence of the Fourier coefficients. (Upper:m=2, Lower:m=from 3 to 10) The abscissa is time with unit of sample number.

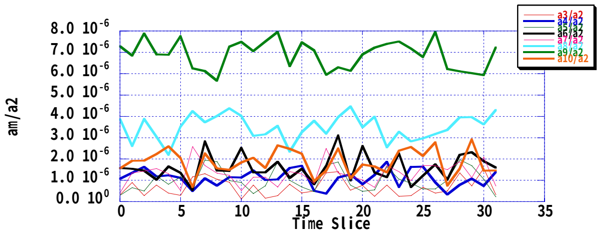

Fig. 8. Time dependence of the Fourier coefficients from m=3 to 10 in the case of 30 kHz signal sampling.

CONCLUSION

A system for measurement of time-dependent multipole fields using a harmonic coil has been developed. Reliability of the basic principle of this system was shown by the simulation where a pure quadrupole field is assumed. It is found that ambiguity of higher multipoles depends on sampling frequency. If the coil signal is stored with the sampling frequency of 20 kHz/S, maximum normalized strength of higher (fake) multipoles is obtained to be less than $1.2\text{x}10^{-5}$. Such a value is sufficiently small for the actual field measurement. In the J-Parc, measurements of time dependence of the multipole fields of quadrupole and sextupole magnets are now being performed.

REFERENCES

[1] Susumu Igarashi, et al., “Magnetic Field Measurement of the J-PARC RCS Steering Magnets and Sextupole Magnets and Comparison to the Field Calculation”, Proceedings of the 3th Accelerator Meeting in Japan, Sendai, Aug. 2-4, 2006.