# BASIC STUDY ON THE REDUCED PLAY MODEL FOR HIGH-SPEED CONTROL OF ACCELERATOR MAGNETS CONSIDERING MAGNETIC HYSTERESIS

**Y. Onchi*, K.Sugahara*, Y.Hane****

*Graduate School of Science and Engineering Kindai University, Japan
**Graduate School of Engineering Tohoku University, Japan
onchi.yoshitake@kindai.ac.jp

**Keywords: Accelerator, real-time simulator, magnetic hysteresis, electromagnet, reduced play model**

## Abstract

In an accelerator system, it is necessary to adjust beam orbits by changing the output magnetic fields with the current values exciting accelerator magnets. However, the magnetic hysteresis is not considered in this beam commissioning process. Instead, the current values are currently modified by trial-and-error. Hence, it is required to establish a prediction method of the current values that reproduce the magnetic fields including the magnetic hysteresis effects. In this paper, the reduced play model (RPM) is proposed. The RPM is constructed by re-identifying the shape functions from the I-B characteristics obtained from a conventional finite element method (FEM) incorporating the dc hysteresis effects. As a result of the examination, it was verified that the proposed RPM speeds up the magnetic field calculations which is fast enough for the usage during the beam commissioning.

## 1 Introduction

An accelerator system generates high-energy particle beams by accelerating charged particles using electric and magnetic fields. Since there are unavoidable some manufacturing errors in the dimensions of accelerator magnets, to irradiate beam as designed, it is required to adjust the output magnetic fields by changing the current values exciting accelerator magnets by trial-and-error. However, at this time, all magnets must be stopped and demagnetized each time this beam commissioning process is performed. This process generally takes more than half a year, which is a significant obstacle to easy operation and low cost of an accelerator system [1]. The magnetic hysteresis is one of the main causes of such long-term beam commissioning.

In the previous studies, various quantitative magnetic hysteresis models have been proposed [2]. Among them, a play model [3,4], which is one of the phenomenological dc hysteresis models, has been extensively studied in the field of electric machines in recent years, because it is capable of high-speed and high-accuracy calculations. However, all these methods have only been applied to electric machines such as electric motors, so far. On the other hand, the magnetic hysteresis is generally recognized as difficult to quantify in the field of accelerators.

Therefore, this study aims to reduce time and cost of beam commissioning by establishing a real-time simulation method considering the hysteresis effects to immediately determine the current values corresponding to the output magnetic fields. In this paper, it is described that the RPM is identified by acquiring I-B characteristics of an accelerator magnet at various current amplitudes from results of the preliminary analysis by a FEM incorporating the dc hysteresis effects by a play model. As a result of the examination, it was found that the proposed method can fast compute the arbitrary hysteresis curves with accuracy comparable to FEM.

## 2 Construction of reduced play model

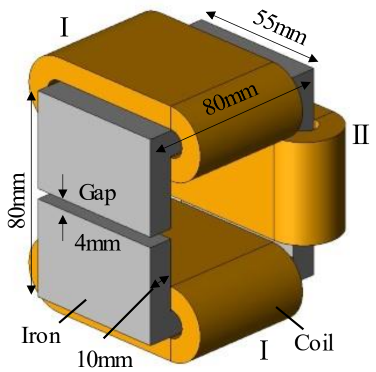


Figure 1: Schematic diagram of a C-shaped electromagnet.

| | |
|---|---|
| Core material | Non-oriented silicon steel (50A700) |
| Coil material | Copper |
| Number of turns | I: 304, II: 244, total: 852 |

Table 1: Specifications of a C-shaped electromagnet.

The analysis is performed using a miniature model of a C-shaped electromagnet for an accelerator magnet, as shown in Figure 1 and Table 1.

In the following, the identification method of the reduced play model is explained. First, magnetic field analysis of a C-shaped electromagnet is performed by an FEM using the play model. For simplicity, eddy currents are neglected in this analysis. Figure 2 shows an example of the stepwise-controlled exciting current waveforms used in the analysis. The maximum current varies are from 0.2 A to 3.0 A at intervals of 0.2 A for each waveform, and the current value changes in increments of 0.2 A for any cases.

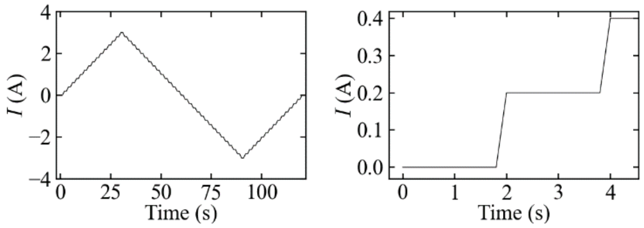


Figure 2: An example of the stepwise-controlled exciting current waveform (left) and its enlarged view (right).

Next, the I-B hysteresis curves are obtained from the values of exciting current and the magnetic flux density at the middle point of air gap of an electromagnet by performing the FEM to identify the novel shape functions for the RPM. The play model generally uses the magnetic flux density *B* as input and the magnetic field *H* as output. However, the RPM uses the current *I* as input and the magnetic flux density *B* as output in this paper. The identical current waveforms in the preliminary analysis using the FEM are applied to the model, and the obtained I-B characteristics are compared with those calculated by the FEM.

## 3 Verification results

This chapter presents the numerical analysis results of the RPM described in Chapter 2 and those of the FEM for comparison. In both the RPM and FEM, the analysis is performed when a C-shaped electromagnet is excited by the current waveform shown in Figure 3, to verify the reproducibility of minor loops. Figure 4 shows the hysteresis curves calculated by the RPM and FEM. As shown in the figure, both results are in good agreement. Therefore, it is demonstrated that the RPM is effective for high-speed and high-accuracy magnetic field calculations, even though only the dc hysteresis effects are considered.

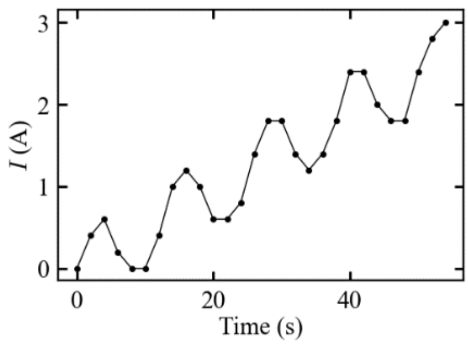


Figure 3: Exciting current waveform to evaluate the representation accuracy of minor loops.

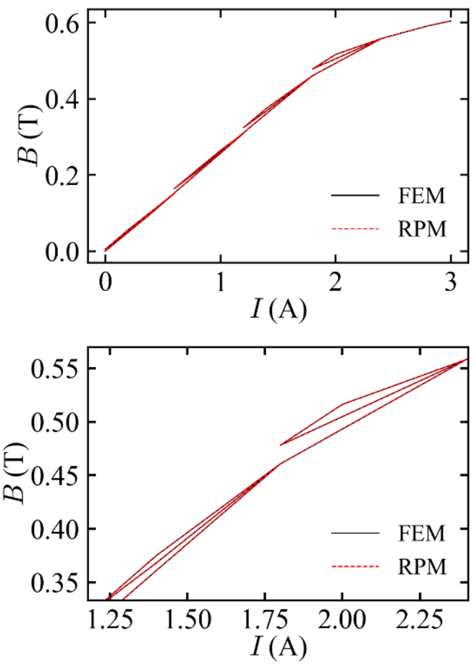


Figure 4: Hysteresis curves depicting minor loops (upper) and their enlarged views (lower).

## 4 Conclusions

In this paper, the RPM was proposed for a real-time simulation of accelerator magnets, and its validity and usefulness were discussed. The analysis results showed that the proposed method could be used to reduce computational time and cost of the existing method while keeping the representation accuracy.

## Acknowledgements

The JSPS KAKENHI Grant-Numbers JP20K04454 supported this work.

## References

[1] Antanas V. Rauchas, Franklin R. Brumwell, Gerald J. Volk. “Commissioning of the Argonne Intense Pulsed Neutron Source (IPNS-I) Accelerator”, *IEEE Trans. Nuclear Science*, **vol. 26**, no. 3, pp. 3006-3008, (1979).

[2] A. Iványi. “Hysteresis Models in Electromagnetic Computation”, *Akadémiai Kiadó*, (1997).

[3] S. Bobbio, G. Miano, C. Serpico and C. Visone. “Models of Magnetic Hysteresis Based on Play and Stop Hysterons”, *IEEE Trans. Magn.*, **vol. 33**, no. 6, pp. 4417-4426, (1997).

[4] J. Kitao, K. Hashimoto, Y. Takahashi, K. Fujiwara, Y. Ishihara, A. Ahagon, and T. Matsuo. “Magnetic Field Analysis of Ring Core Taking Account of Hysteretic Property Using Play Model”, *IEEE Trans. Magn.*, **vol. 48**, no. 11, pp. 3375-3378, (2012).