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Nonlinear Magnetic Circuit Analysis of SMART Control Rod Drive Actuator

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1. Introduction

Magnetic circuit modeling is a useful tool when designing an electromagnetic actuator, as it allows fast calculations and enables parametric studies. It is particularly essential when the actuator is to be used in a very complex system such as a nuclear reactor. Important design parameters must be identified at the early stage of the design process. Once the design space is narrowed down, more accurate methods such finite-element analyses (FEA) can be employed for detailed design.

Magnetic circuit modeling is based on the assumption that a flux path consists of sections in each of which field quantities are constant with linear constitutive relations. This assumption fails to hold when portions of the flux path become saturated. The magnetic circuit must be modified in order to accurately describe the nonlinear behavior of saturation.

In this paper, we derive a nonlinear magnetic circuit model of an electromagnetic control-rod actuator in the SMART. The results of the nonlinear model are compared with those by linear circuit model and finite-element analyses.

2. Modeling of Control Rod Actuator

2.1 Linear Circuit Model

A control rod drive actuator is an electromagnetic device which drives a control rod assembly linearly to regulate the reactivity of a nuclear core. Fig. 1 shows the schematic of the control rod drive in SMART [1]. Inside the motor housing, the plungers and the drive shaft are operating in a high-temperature, high-pressure environment. The actuators including coils are placed outside the motor housing. The magnetic flux must be delivered to the plungers and poles in order to generate necessary forces. Therefore, the motor housing should be made of magnetic materials. Various combinations of the lift and latch actuations hold, lift, or lower the drive shaft which is connected to the control rod.

Illustrated in Fig. 2 is a simplified geometry of the control rod drive actuator. The stationary latch part is not considered for brevity, but it can be easily added to the model if necessary. Using the definition of the magnetic reluctance

$$R = \int \frac{dl}{\mu A} \tag{1}$$

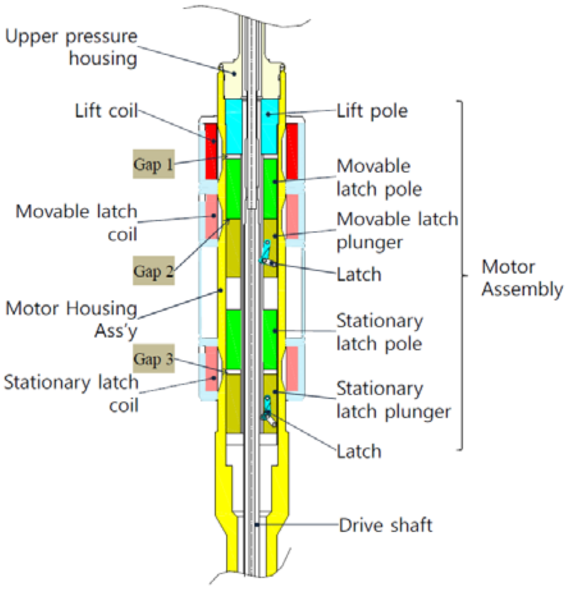

Fig. 1. Configuration of the control rod drive actuator in SMART [1]

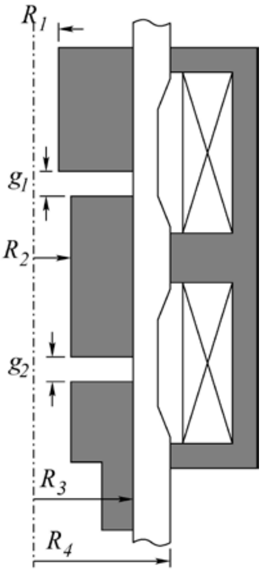

Fig. 2. Simplified geometry of the control rod drive actuator

the sections of magnetic flux paths can be modeled as having fixed reluctances. Shown in Fig. 3 is the circuital representation of the magnetic flux paths. For example, the reluctance R_1 is the main branch of the lift actuator, while F_1 is the magneto-motive force of the lift coil. If the material is linear, the permeability μ in (1) is constant and independent from the magnetic flux level. Applying the Ampere's circuital law and the conservation of flux, we get a set of linear equation expressed as

$$\mathbf{R}\Phi = \mathbf{F} \tag{2}$$

where **R** is the reluctance matrix and **F** is the magneto-motive force vector. Inverting the reluctance matrix, we can obtain the magnetic fluxes. The lifting force of the actuator is obtained from

$$F_{\text{lift}} = \frac{\phi_2^2}{2\mu_0 A_{\text{lift pole}}} \tag{3}$$

2.2 Nonlinear Circuit Model

If the material is magnetically saturated, the permeability decreases significantly. There are several saturation models in the literature, but in this paper we use a heuristic nonlinear saturation model in the form of

$$H = \frac{B}{\mu_0 \bar{\mu}_r} + \frac{\sigma}{\mu_0}\left(1 - \frac{1}{\bar{\mu}_r}\right)\ln\left[1 + \eta\, e^{(B-\beta)/\sigma}\right] \tag{4}$$

The parameters, $\bar{\mu}_r$, β, σ, and η can be determined by curve-fitting the model of (4) with the magnetization curve obtained from test samples. If the saturation model is used, the linear circuit model of (2) must be modified as

$$\Phi = \mathbf{R}^{-1}(\Phi, g)\mathbf{F} \tag{5}$$

Now, the reluctance matrix is a function of not only the gaps, but also the flux levels. This model must be iteratively solved in order to find the solution.

3. Results and Discussions

Fig. 4 shows the results of the analyses. The actuator forces with respect to the gap 1 in Fig. 1 are calculated using the nonlinear circuit model and compared with the results from FEA as well as from linear circuit model. As the gap increases, the nonlinear and linear results tend to match well with FEA results.

However, at the smallest gap, the discrepancy between the linear results and FEA is increasing, while the nonlinear results continue to match well with FEA. As the gap decreases, the material becomes more saturated, especially at thin sections of the motor housing. Therefore, a nonlinear magnetic circuit model must be used for proper prediction of actuator forces irrespective of air gap lengths.

REFERENCES

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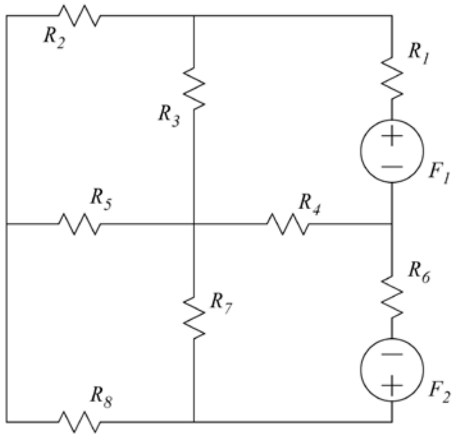

Fig. 3. Magnetic circuit model of the actuator

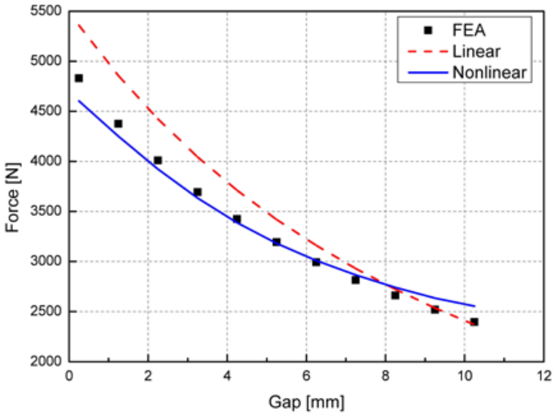

Fig. 4. Results from nonlinear magnetic circuit, linear magnetic circuit and finite-element analyses

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