Magnetic Field Analysis of Self-propelled Rotary Actuator's Stator by using Vector Magnetic Property Utilization Technique

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In this paper, in order to improve the self-propelled rotary actuator whose rotational axis is parallel to the exciting magnetic field, the magnetic field analysis of the actuator's stator is carried out. The actuator's stator is constructed from silicon steel sheets, the rolling direction of the silicon steel sheet can be taken into consideration in magnetic field analysis by using the complex E&S model which is one of the vector magnetic property utilization technique. The rotational magnetic flux has occurred in the silicon steel stator when a magnetic field is applied to the direction different from the rolling direction. It is expected that the rotational magnetic flux which occurs in the silicon steel stator contributes to rotate the rotor smoothly. Consequently, we estimate the suitable setting direction of the rolling direction in the actuator's silicon steel stator by this analysis.

***Index Terms*—Actuator, E&S model, finite element method, rolling direction, silicon steel sheet, vector magnetic property.**

I. Introduction

IN ORDER to detect the defects inside of a tube in the industrial plants as typified by nuclear power plants and nuclear fusion reactors, it is necessary to develop an actuator self-propelled inside of the tube. To self-propel inside of the tube, rotational motion with a screw is the most effective method to produce the driving force of an actuator. In general, an actuator like a motor is rotated by the magnetic field applied in the perpendicular direction to rotational axis. As shown in Fig. 1, although it is easy to install an exciting coil on the outside of a tube, a magnetic field is induced in parallel to the axis direction of a tube by the coil. Therefore, as shown in Fig. 2, we have fabricated the self-propelled rotary actuator whose rotational axis is parallel to the exciting magnetic field [1]-[2]. In this actuator, six permanent magnets are fixed on the rotor which is cylinder made from acrylic. The stator has six pole pieces which are made of grain-oriented silicon steel sheet (35G155). Magnetic poles are induced simultaneously in the both edges of the silicon steel stator by exciting magnetic field $\boldsymbol{H}_o$ as shown in Fig. 2(a). The rotor rotates because the magnet on the rotor circumference receives the attracting force from the magnetic pole induced to the stator. Moreover, the N and S magnetic pole of the stator change alternately by applying alternating current to the solenoid coil.

However the starting torque of this actuator is still small and the rotating direction is unstable. It is thought that the main causes of this problem are how to use the silicon steel sheets of the stator of the actuator. When the rolling direction of a silicon steel sheet is set in parallel with the direction of the exciting magnetic field $\boldsymbol{H}_o$ as shown in Fig. 3(a), the magnetic flux distribution in a silicon steel stator is symmetrical with respect to the rotational axis. Consequently, because the attracting force which the magnet of the rotor receives is also symmetrical with respect to the rotational axis, the starting torque of the rotor is small and the rotating direction is unstable. In order to solve this problem, it is necessary to set the rolling direction in the different direction from the exciting magnetic field as shown in Fig. 3(b), and to distribute the magnetic flux in the silicon steel stator unsymmetrically. Furthermore, it has been reported that rotational magnetic flux occurs in the silicon steel sheet when a magnetic field is applied to the direction different from the rolling direction [3]. Therefore, it is expected that the rotational magnetic flux which occurs in the silicon steel stator contributes to rotate the rotor smoothly. When carrying out magnetic field

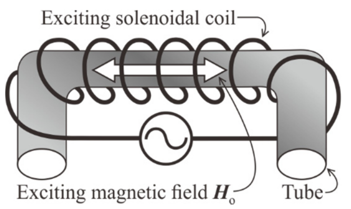


Fig. 1. An exciting coil installed on the outside of a tube.

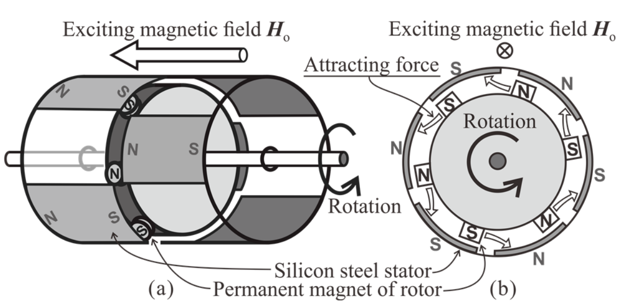


Fig. 2. Structure of the self-propelled rotary actuator. (a) Whole figure of the actuator. (b) Cross-section view in the central part of the actuator.

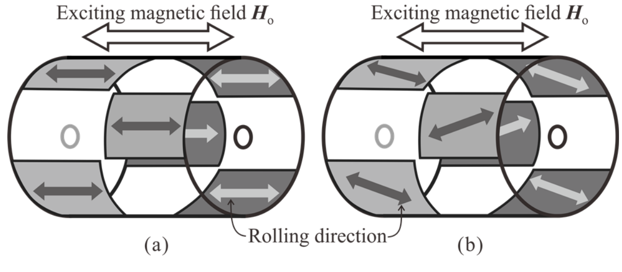


Fig. 3. Relation between the rolling direction and the exciting magnetic field. (a) The rolling direction is parallel to the exciting magnetic field direction. (b) The rolling direction is inclined from the exciting magnetic field direction.

analysis in consideration of the rolling direction, it is effective to introduce the vector magnetic property utilization technique to the analysis. In this paper, the magnetic field analysis of self-propelled rotary actuator's stator is carried out by using the complex E&S model which is one of a vector magnetic property utilization technique. We estimate the suitable setting direction of the rolling direction by using the magnetic field analysis which introduced the complex E&S model, when using a silicon steel sheet as the actuator's stator.

II. Vector Magnetic Property Utilization Technique

We carry out magnetic field analysis which introduced the complex E&S model. The complex E&S model can be expressed as follows [4]:

$$\begin{cases} \dot{H}_x = \bar{\nu}_{xr}(B_{\max},\theta_B,\alpha,f_0)\dot{B}_x + j\omega\bar{\nu}_{xi}(B_{\max},\theta_B,\alpha,f_0)\dot{B}_x \\ \dot{H}_y = \bar{\nu}_{yr}(B_{\max},\theta_B,\alpha,f_0)\dot{B}_y + j\omega\bar{\nu}_{yi}(B_{\max},\theta_B,\alpha,f_0)\dot{B}_y \end{cases}, \quad (1)$$

where, $\bar{\nu}_{xr}$, $\bar{\nu}_{yr}$ are the magnetic reluctivity coefficients and $\bar{\nu}_{xi}$, $\bar{\nu}_{yi}$ are the magnetic hysteresis coefficients. The point on a variable indicates a complex value and the bar on a variable indicates an effective value. The vector magnetic properties are defined by three parameters $B_{\max}$, θ_B, and α which are the maximum magnetic flux density, the inclination angle, and the axis ratio, respectively. f_0 is the frequency of exciting magnetic field. The coefficients $\bar{\nu}_{xr}$, $\bar{\nu}_{yr}$, $\bar{\nu}_{xi}$, and $\bar{\nu}_{yi}$ are given by

$$\begin{cases} \bar{\nu}_{xr} = \left\{|\dot{H}_x| / |\dot{B}_x|\right\}\cos(\theta_{BHx}),\ \bar{\nu}_{xi} = \left\{|\dot{H}_x| / \left(\omega|\dot{B}_x|\right)\right\}\sin(\theta_{BHx}) \\ \bar{\nu}_{yr} = \left\{|\dot{H}_y| / |\dot{B}_y|\right\}\cos(\theta_{BHy}),\ \bar{\nu}_{yi} = \left\{|\dot{H}_y| / \left(\omega|\dot{B}_y|\right)\right\}\sin(\theta_{BHy}) \end{cases}, \quad (2)$$

where θ_{BHx} and θ_{BHy} are the phase difference between $\dot{B}_x$ and $\dot{H}_x$ and between $\dot{B}_y$ and $\dot{H}_y$, respectively.

III. Analysis Results of Actuator's Stator

In this paper, we define the inclination angle ϕ between the rolling direction in the actuator's silicon steel stator and the exciting magnetic field direction, as shown in Fig. 4. Fig. 5 shows the distribution of the magnetic flux line. In Fig. 5(a), the rolling direction of the silicon steel sheet is set in parallel to the direction of exciting magnetic field. Both ϕ_1 and ϕ_2 is 0 (deg.). In this case, the distribution of the magnetic flux in the silicon steel stator is symmetrical. However, as shown in Fig. 5(b), magnetic flux is unsymmetrical when ϕ_1 and ϕ_2 is set as −45 (deg.) and 45(deg.), respectively.

Fig. 6 shows the distribution of the axis ratio α of rotational magnetic flux density in the silicon steel stator. In Fig. 6(a), the magnetic flux density is almost alternating flux condition. On the other hand, as shown in Fig. 6(b), the elliptical magnetic flux density has occurred near the pole of the silicon steel stator. Moreover, the elliptical magnetic flux density in the stator can expect to contribute to improvement in starting torque since the elliptical magnetic flux density distribution is unsymmetrical with respect to the rotational axis of the rotor.

IV. Conclusions

In order to improve the self-propelled rotary actuator whose rotational axis is parallel to the exciting magnetic field, we carry out the magnetic field analysis of the actuator's stator by using vector magnetic property utilization technique. As a result, we can confirm that the rotational magnetic flux has occurred in the silicon steel stator when a magnetic field is applied to the direction different from the rolling direction. Moreover, we can propose the novel design method for the actuator by using vector magnetic property utilization technique.

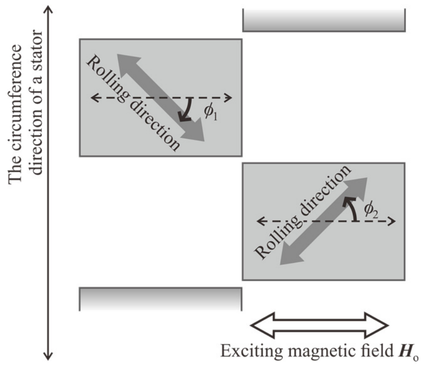
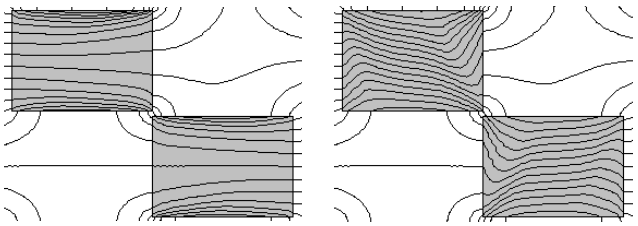
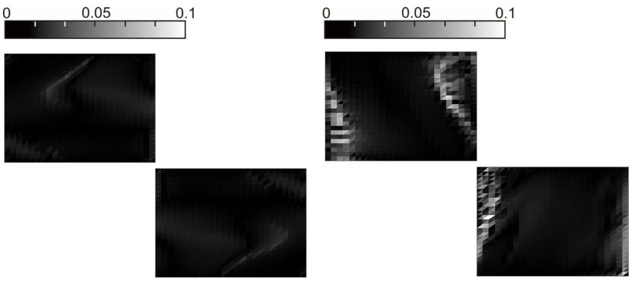


Fig. 4. The definition of the inclination angle ϕ of the rolling direction in the actuator's silicon steel stator.



(a) $\phi_1 = 0,\ \phi_2 = 0$ [deg.] (b) $\phi_1 = -45,\ \phi_2 = 45$ [deg.]

Fig. 5. The distribution of the magnetic flux line in the actuator's stator.



(a) $\phi_1 = 0,\ \phi_2 = 0$ [deg.] (b) $\phi_1 = -45,\ \phi_2 = 45$ [deg.]

Fig. 6. The distribution of the axis ratio α of rotational magnetic flux density in the actuator's stator.

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