Control of an Interior Permanent Magnets Screw Motor with Power-saving Axial-gap Displacement Adjustment

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Abstract—This paper proposes position and force control of a screw motor with power-saving axial-gap displacement adjustment. The motor has a helical-shape mover, which moves in a helical-shape stator without contact. Due to the fabrication process, the actual helical shapes of the mover and the stator are not completely uniform and the air-gap length between the mover and the stator slightly changes depending on the mover rotation angle. The d-axis current remains a finite value and copper loss arises even when the mover is located at the center between the stator cores. A power-saving axial-gap displacement adjustment method is proposed to solve this problem. The proposed control is experimentally verified.

Index Terms—Electric motors, AC motors, permanent magnet motors, servomotors, linear motors, linear actuators, helical-motion motors, screw motors, spiral motors, gap displacement adjustment, motion control.

I. INTRODUCTION

In many advanced nations, due to recent low birthrate and longevity, reduction in labor force and increase in elderly people are becoming a social issue. Manual assist manipulators or lift assist devices with vacuum gripper end-effectors have been widely introduced in production area to handle heavy loads easily. In hospitals and nursing homes, patient lifts are provided for transfers of patients with mobility problems between a bed and a wheelchair. These devices have very limited functions and are too big to use in a small room. Recently, more general assistive devices than ever have been developed. A powered exoskeleton provides mobility assistance for infirm people[1]. Actuators for assistive devices are required to be compact, high-power, safe, and compliant. Especially safety issue is big concern because the devices directly interact with the users. A compliant actuator is defined as an actuator that allows deviations from its own equilibrium position depending on the applied external force[2]. Conventionally, combination of electric rotary motor and high-reduction-ratio gears such as harmonic gears are widely used for robotic application.

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The equivalent output inertia drastically increases in inversely proportional to the square of the reduction ratio. This results in a large impulse when the robot collides with a human.

Several approaches have been proposed to overcome this problem. A light-weight robot arm equipped with the *DLR*¹ *actuators* for assistive tasks reduces risk of collision[3]. The actuator is designed so that the total volume becomes minimal and the load torque can be measured by strain gauge-based sensors mounted on the *flex spline* of the harmonic drive or specially designed beams between the reduction gear and the load. Another approach to reduce impact is series elastic actuators (SEAs)[2][4]–[6]. Springs are installed between a output link and a geared motor. Inertia of the output link and the geared motor are almost decoupled by the springs. Therefore the equivalent output inertia of the actuator does not increase. In addition, these approaches recover the backdrivability of the actuator. However these actuators have a disadvantage of narrow bandwidth of the control systems. Sensing bandwidth of the DLR actuator is limited up to 600Hz. The control bandwidth of the SEA is less than about one-third of the fundamental resonant frequency, which is typically in the range of 100Hz or less. These performances are not enough compared with existing direct-drive actuators.

Pure direct-drive system is almost free from backlash and friction and easy to realize for precise, high-speed, and safe motion. Therefore, from the viewpoint of controllability, the direct-drive systems are suitable for robotics applications. However, conventional direct-drive motors have low load to weight ratio and are too heavy to be installed in assistive devices. Recently, many works on permanent magnet (PM) linear motors have been reported[7]–[19]: tubular linear motors[7]–[10], switched flux linear motors[11], etc. Some of them deal with design issue of PM linear motors[12]–[15]. Other works on high-temperature superconducting linear motors have been reported[20]. An application of linear motors for haptic devices has been reported[21] where direct-drive feature has an important role in their control systems. Linear actuators using magnetic screw-nut have been proposed[22]–[24], in which helically disposed, radially magnetised permanent magnets are placed on both the screw and the nut. Various types of a 2-DOF motor capable of producing rotary and linear motion have been presented in articles[25]–[36]. There are stepper motors[25][26], induction motors[27][28], reluc-

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Fig. 1. Structure of IPM screw motor.

tance motors[29][30], permanent-magnet motors[31]–[34], and piezoelectric actuators[35][36]. All these 2-DOF motors are radial-gap motors.

There are several approaches to improve the thrust force of linear motors. Thrust force is directly proportional to gap area and inversely proportional to gap length. A method to expand gap area without increasing volume is to design a motor of a special 3-D structure. Authors have proposed a new helical structure of a direct-drive system that meets the requirements of safety, performance, and compactness[37]–[41]. The motor has a helical-shape mover, which moves in a helical-shape stator without contact. Compared with existing rotary-motor-driven ballscrew systems, the proposed motor has advantages in terms of safety, compliance, and controllability. However, due to the fabrication process, the actual helical shape of the motor is not completely uniform and the air-gap length between the mover and the stator slightly changes depending on the mover rotation angle. Therefore, the equilibrium point of magnetic attractive force between mover magnets and stator core is not determined easily. The current remains a finite value and copper loss arises when the mover tries to keep axial-gap displacement constant which corresponds to non-equilibrium point. In this paper, a power-saving axial-gap displacement control is proposed to solve this problem. The zero-power controls for existing levitating machines have been reported[42]–[44]. In this paper, similar to the zero-power control, a new power-saving axial-gap displacement control for the screw motor is proposed. The proposed control is verified by a couple of experiments.

(a) Exterior of IPM screw motor.

(b) Mover of IPM screw motor.

(c) Stator of IPM screw motor.

Fig. 2. Prototype of IPM screw motor.

II. SCREW MOTOR

A. Design

Fig. 1 shows a model of an interior permanent magnet (IPM) type screw motor. The blue part is a helical mover in which permanent magnets colored in the orange are inserted in the mover core made of high-permeability soft-magnetic free-cutting steel MES3F, made by Tohoku Steel, co. ltd, that contains 2.7% silicon and 0.2% lead, making it very easy to machine. The shaft colored in the purple is made of non-magnetic material. Dominant flux of the magnets goes along with the axial direction. The cyan part is a helical stator in which slots are provided for two three-phase windings. Fig. 1 (c) is a schematic view showing the allocation of the stator windings. The stator is made of bulk steel same as the mover and fabricated by machine tools. Therefore eddy current losses in the stator are higher than those of laminated iron core or soft magnetic composite core. Each of windings interacts with the magnet in the mover iron. The motor is a sort of axial-gap permanent magnet synchronous machine. Linear-rotary bearings are installed between the mover and the stator to share the rotating axis and to support the mover against radial

load force. Therefore the motor has two-degree of motion freedom. One is rotary motion around the axis, and the other is linear motion along with the axis. Each motion is almost independent but subject to limited space of the narrow air gaps. Fig. 2 (a), (b), and (c) show the exterior, the mover, and the stator of a prototype of the screw motor, respectively. As an end-effector of the motor, a rotation cancellation mechanism consisting of angular bearings is attached at the end of the mover shaft to cancel rotary motion and extract linear motion only. In addition, the motor is equipped with a rotary encoder and a linear encoder to measure the rotation angle and linear position of the mover, respectively.

B. Model

1) *Voltage Equation:* Voltage equation of the screw motor can be derived from magnetic circuit of the motor[39]. For simplicity, we assume that the iron core is made of linear magnetic material and the permeability of the permanent magnet is equivalent to the permeability of free space. It is also assumed that the edge effect is negligible and the permanent magnets produce a sinusoidally varying magnetic field on concentrated windings. These assumptions give a rough approximation of the actual model, which is sufficient for employing in control system if we conduct parameter identification.

The dq-axis voltage equations for each three-phase windings are represented by

$$\begin{bmatrix} V_{1d} \\ V_{1q} \end{bmatrix} = \begin{bmatrix} R + L_{1d} \left(\frac{d}{dt} \right) & 0 \\ 0 & R + L_{1q} \left(\frac{d}{dt} \right) \end{bmatrix} \begin{bmatrix} I_{1d} \\ I_{1q} \end{bmatrix} + \begin{bmatrix} \dot{x}_g L_{1d}/l_1 & -p\dot{\theta} L_{1q} \\ p\dot{\theta} L_{1d} & \dot{x}_g L_{1q}/l_1 \end{bmatrix} \begin{bmatrix} I_{1d} \\ I_{1q} \end{bmatrix} + \Psi_1 \begin{bmatrix} \dot{x}_g/l_1 \\ p\dot{\theta} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} V_{2d} \\ V_{2q} \end{bmatrix} = \begin{bmatrix} R + L_{2d} \left(\frac{d}{dt} \right) & 0 \\ 0 & R + L_{2q} \left(\frac{d}{dt} \right) \end{bmatrix} \begin{bmatrix} I_{2d} \\ I_{2q} \end{bmatrix} + \begin{bmatrix} -\dot{x}_g L_{2d}/l_2 & -p\dot{\theta} L_{2q} \\ p\dot{\theta} L_{2d} & -\dot{x}_g L_{2q}/l_2 \end{bmatrix} \begin{bmatrix} I_{2d} \\ I_{2q} \end{bmatrix} + \Psi_2 \begin{bmatrix} -\dot{x}_g/l_2 \\ p\dot{\theta} \end{bmatrix} \quad (2)$$

where V_{id} and V_{iq} are the d-axis and q-axis voltage, I_{id} and I_{iq} are the d-axis and q-axis current of the windings, respectively. Subscript $i = \{1, 2\}$ represents the section of the magnetic circuit; "1" corresponds to the back-side windings and "2" corresponds to the front-side windings. L_{id} and L_{iq} are the d-axis and q-axis inductance, respectively. R is the winding resistance on d-axis and q-axis. Ψ_i is the field by the permanent magnets. p is the number of pole pairs per 360 degree mechanical angular displacement. x_g is the displacement of air gap; $x_g = 0$ when the mover is at the center between the stator cores. x is the linear position of the mover. θ is the mechanical rotational angle of the mover. $l_1 = l - x_g$ is the air gap between the back-side stator core and the front-side mover core, and $l_2 = l + x_g$ is the air gap between the front-side stator core and the back-side mover core, where l is nominal air gap. This voltage equations are almost similar to those of conventional rotational synchronous motors except the terms of $\dot{x}_g$, velocity of the gap displacement.

2) *Motion Equation:* Motion equation of the screw motor is obtained from the same magnetic circuit.

$$M\ddot{x} = qp(f_1 + f_2) - f_{dis} \quad (3)$$

$$J\ddot{\theta} = qp(\tau_1 + \tau_2) \quad (4)$$

where f_1 and τ_1 are thrust-force and torque acting between the back-side stator core and the front-side mover core, respectively, and f_2 and τ_2 are those acting between the front-side stator core and the back-side mover core, respectively. They are given by

$$f_1 = \frac{1}{l_1} \Psi_1 I_{1d} + \frac{1}{2l_1} (L_{1d} I_{1d}^2 + L_{1q} I_{1q}^2 + L_{1f} I_{1f}^2) \quad (5)$$

$$\tau_1 = p(\Psi_1 I_{1q} + (L_{1d} - L_{1q}) I_{1d} I_{1q}) - hf_1 \quad (6)$$

$$f_2 = -\frac{1}{l_2} \Psi_2 I_{2d} - \frac{1}{2l_2} (L_{2d} I_{2d}^2 + L_{2q} I_{2q}^2 + L_{2f} I_{2f}^2) \quad (7)$$

$$\tau_2 = p(\Psi_2 I_{2q} + (L_{2d} - L_{2q}) I_{2d} I_{2q}) + hf_2 \quad (8)$$

where M , J are mass and inertia of the mover, respectively. f_{dis} is disturbance force applied to the mover. $h = l_p/2\pi$ is an axial screw length per rotation angle in radian where l_p is lead of the screw which is an axial travel of the screw during a single revolution. q is the number of layers of the screw. I_{if} is the equivalent field current by the permanent magnets and L_{if} is the corresponding self-inductance. Previously defined Ψ_i , the field by the permanent magnets, corresponds to a product of I_{if} and the mutual inductance between I_{if} and I_{id} .

The gap displacement x_g , the linear position x , and the rotation angle θ have a relation such that:

$$x_g = x - h\theta \quad (9)$$

subject to $|x_g| \leq l_g$ where l_g is the maximum gap displacement. If the gap displacement x_g is controlled to be zero, then the mover is located at the center between the stator cores and $x = h\theta$ holds from (9). This relationship corresponds to the ideal screw in which the rotation angle θ is in proportion to the linear position x .

With a back EMF compensation and the PI current feedback, the currents of the windings can be controlled stably within 1ms. The back EMF, the second and third terms of the right-hand sides of (1) and (2), can be cancelled by adding these calculated values to the voltage references for V_{id} and V_{iq} . By using the current controller, we can control each current such that $I_d^{ref} = I_{1d} = -I_{2d}$ and $I_q^{ref} = I_{1q} = I_{2q}$. Then, the motion equation (3)(4) can be approximated and simply rewritten as follows.

$$M\ddot{x} = K_f I_d^{ref} + K_g(x_g - x_{g0}) - f_{dis} \quad (10)$$

$$J\ddot{\theta} = K_\tau I_q^{ref} - hK_f I_d^{ref} - hK_g(x_g - x_{g0}) \quad (11)$$

where K_f and K_τ are thrust and torque constants, respectively. K_g is a negative spring coefficient due to the magnetic attractive force acting between the permanent magnet and the stator iron core. x_{g0} is introduced to represents equilibrium point of the gap displacement which is ideally zero.

Fig. 3. Block diagram of position control system with power-saving axial-gap displacement adjustment.

3) *Gap Dynamics*: Dynamics of the gap displacement can be derived from (10) and (11) as follows.

$$M\ddot{x}_g = (1 + rh)(K_f I_d^{ref} + K_g(x_g - x_{g0}) - rK_\tau I_q^{ref} - \hat{f}_{dis}) \quad (12)$$

where $r = hM/J$. Assume that the term rh is small enough, i. e., $rh \ll 1$, then we have

$$M\ddot{x}_g = K_f I_d^{ref} - K_{f2} I_q^{ref} + K_g(x_g - x_{g0}) - \hat{f}_{dis} \quad (13)$$

where $K_{f2} = rK_\tau$. Note that dynamics of the gap displacement (13) is similar to that of the linear motion (10), however it is affected by the q-axis current.

Note that $L_{id} = L_{iq}$ holds because the screw motor in this paper does not have saliency while it is an IPM type motor.

C. Control

1) *Power-saving Axial-gap Displacement Control*: In order to realize direct-drive motion, axial-gap displacement control is applied to the screw motor. When the axial-gap displacement controller stabilizes the axial-gap, the mover does not contact to the stator except fringes that support the mover shaft. Therefore the mover is almost free from backlash and friction. Based on the model (13), the d-axis current is determined to stabilize the gap displacement as follows.

$$I_d^{ref} = \frac{1}{K_{fn}} (M_n \ddot{x}_g^{ref} - K_{gn} x_g + K_{f2n} I_q^{ref} + \hat{f}_{dis}) \quad (14)$$

$$\ddot{x}_g^{ref} = K_{gp}(x_g^{ref} - x_g) + K_{gd}(\dot{x}_g^{ref} - \dot{x}_g). \quad (15)$$

The subscript n represents nominal parameters. The gain K_p and K_d are chosen such that $M_n s^2 + K_d s + K_p$ is stable. $\hat{f}_{dis}$

is estimated disturbance by the disturbance observer:

$$\hat{f}_{dis} = \frac{\omega_d}{s + \omega_d} (K_{fn} I_d^{ref} + K_{gn} x_g - K_{f2} I_q^{ref} - M_n s \dot{x}_g). \quad (16)$$

As the result, the dynamics of the gap displacement follows the model:

$$\ddot{x}_g = K_{gp}(x_g^{ref} - x_g) + K_{gd}(\dot{x}_g^{ref} - \dot{x}_g) - K_g x_{g0} - (\hat{f}_{dis} - \hat{f}_{dis}). \quad (17)$$

Copper loss arises when the axial-gap displacement controller tries to keep the axial-gap displacement at non-equilibrium point. In order to solve this problem, power-saving axial-gap displacement control is proposed here. To find the equilibrium gap displacement x_{g0} , the reference of the gap displacement is given by

$$x_g^{ref} = K_z \int I_d^{ref} dt \quad (18)$$

$$\dot{x}_g^{ref} = K_z I_d^{ref} \quad (19)$$

where K_z is the gain of the controller. The gap reference x_g^{ref} is expected to converge to the equilibrium point and the d-axis current I_d^{ref} converge to zero. From (10), the d-axis current I_d^{ref} and the gap displacement x_g have opposite sign in the steady state. Therefore, if $x_g > x_{g0}$ then $I_d^{ref} < 0$ and the gap reference x_g^{ref} in (18) decreases until x_g^{ref} reaches x_{g0} .

2) *Position Control*: Various type of control, such as position control, force control, etc., can be realized by using the q-axis current I_q after applying the above mentioned axial-gap displacement control. In this section, position control is proposed.

Fig. 6. Power-saving axial-gap displacement control.

Fig. 7. Position control with power-saving axial-gap displacement control. (step reference)

Fig. 8. Position control without power-saving axial-gap displacement control. (step reference)

estimator[46] as follows,

$$\ddot{x}^{ref} = K_{fp} (f^{cmd} - \hat{f}^{rec}) \quad (26)$$

$$\hat{f}^{rec} = \frac{\omega_f}{s + \omega_f} \left(K_{fn} I_d^{ref} + K_{gn} (x_g - x_{g0}) - K_{f2n} I_q^{ref} - M_n s \dot{x}_g \right). \quad (27)$$

The block diagram of the whole force control system is shown in Fig. 4.

III. EXPERIMENTS

Experiments were conducted to verify the proposed axial-gap displacement control, position control, and force control described in the section II-C. The parameters are shown in Table I. Apparatus for experiments are shown in Fig. 5 and Table II. A rotary encoder attached to the mover shaft generates 5000 pulses/r. The resolution of the rotary encoder is $\pi/10000$ rad using quad edge evaluation method. A linear encoder is attached to the motor with a resolution of $1 \mu\text{m}$ using quad edge evaluation method. Two independent three-phase inverters, working at a 15-kHz switching frequency, are used for driving the screw motor. Three-phase currents are measured using two current sensors and captured into a DSP via A/D converter board at every sampling period of $66.7 \mu\text{s}$.

TABLE I
PARAMETERS

Mass of the mover	$M[\text{kg}]$	0.7
Inertia of the mover	$J[\text{kgm}^2]$	0.00022
Thrust constant (I_d)	$K_f[\text{N/A}]$	18.4
Thrust constant (I_q)	$K_{f2}[\text{N/A}]$	0.557
Magnetic constant	$K_g[\text{N/m}]$	157000
Torque constant	$K_\tau[\text{Nm/A}]$	0.05
Lead length of screw	$l_p[\text{mm}]$	22
The number of pole pairs per 360 degree	p	2
The number of layers of screw	q	4
Stroke	$[\text{mm}]$	44
Nominal gap length	$l_g[\text{mm}]$	1
Control sampling period	$[\mu\text{s}]$	66.7
PWM carrier frequency	$[\text{kHz}]$	15
Resolution of linear encoder	$[\mu\text{m}]$	1
Resolution of rotary encoder	$[\text{rad}]$	$\pi/10000$
Proportional gain for gap displacement control	K_{gp}	20000
Derivative gain for gap displacement control	K_{gd}	282
Proportional gain for position control	K_{pp}	20000
Derivative gain for position control	K_{pd}	282
Proportional gain for force control	K_{fp}	0.1
Observer gain (x_g)	$\omega_d[\text{rad/s}]$	1000
Observer gain (θ)	$\omega_{dr}[\text{rad/s}]$	1000
Reaction force observer gain	$\omega_f[\text{rad/s}]$	1000
Integral gain for power-saving gap control	K_z	0.0002

(a) Response of the mover position.

(b) Response of the gap displacement.

(c) Response of the currents.

Fig. 9. Position control. (long stroke reference, without load)

(a) Response of the mover position.

(b) Response of the gap displacement.

(c) Response of the currents.

Fig. 10. Position control. (long stroke reference, with load)

(a) Response of the mover position.

(b) Response of the gap displacement.

(c) Response of the currents.

Fig. 11. Position control. (sinusoidal reference)

TABLE II
EXPERIMENTAL SETUP

Unit name	Model designation	Manufacturer
Linear encoder	LIE5 1PL3FD	SUMTAK
Rotary encoder	MEH30-5000PE	Microtech Laboratory
Controller	MW-PE3	Myway Plus
Load cell	9301B	KISTLER
Load motor	S500Q	GMC Hillstone

A. Power-saving Axial-gap Displacement Control

Fig. 6 shows experimental results of the power-saving axial-gap displacement control. Initially, the mover is in a touch-down state due to the magnetic force. Once the gap displacement control (14)–(16) is activated, the mover stably levitated at the center of the air gap where the gap reference x_g^{ref} is set to zero. The power-saving axial-gap displacement control (18)(19) is activated at $t = 1$ s, then the gap reference changes so that the d-axis current goes to zero.

B. Position Control

Fig. 7–11 show experimental results of the position control.

The step references are given in Fig. 7 and 8. In these experiments, the mover is initially in a levitating state by the axial-gap displacement control with the power-saving axial-

gap displacement control in Fig. 7 and without the power-saving axial-gap displacement control in Fig. 8. Almost same position responses are obtained as shown in Fig. 7 (a) and Fig. 8 (a). The gap responses under the power-saving axial-gap displacement control vary according to the change of the equilibrium point as shown in Fig. 7 (b). The proposed power-saving axial-gap displacement control successfully achieves zero d-axis current convergence as shown in Fig. 7 (c) while the d-axis current under the non-power-saving axial-gap displacement control remains a certain value as shown in Fig. 8 (c).

Fig. 9 shows a long stroke response under the position control with the power-saving axial-gap displacement adjustment. The linear position of the mover accurately follows the reference as shown in Fig. 9 (a). In Fig. 9 (b), the gap displacement follows the reference generated by power-saving axial-gap displacement controller. During the acceleration and deceleration periods, the gap displacement goes to the equilibrium point between the permanent magnet force and inertial force. Thus, the wave form in Fig. 9 (b) is similar to the acceleration pattern. In Fig. 9 (c), zero d-axis current is achieved in the steady state and there are transient states during the accelerating and decelerating motion due to the delay of the power-saving axial-gap displacement control. Meanwhile, the q-axis current drives the mover. The accelerating and

(a) Response of the thrust-force. (reference value: 30 N)

(b) Response of the gap displacement.

(c) Response of the currents.

Fig. 12. Force control with power-saving axial-gap displacement control.

(a) Response of the thrust-force. (reference value: 30 N)

(b) Response of the gap displacement.

(c) Response of the currents.

Fig. 13. Force control without power-saving axial-gap displacement control.

decelerating force of the mover are generated by the q-axis current.

Fig. 10 shows similar experimental results of a long stroke response under the position control under load force of 30N generated by the load motor. The load motor is controlled to generate constant thrust force. Fig. 10 (a) shows position response, Fig. 10 (b) shows gap displacement, and Fig. 10 (c) shows d-axis and q-axis currents. Fluctuations of gap displacement and currents are relatively bigger than the case in Fig. 9 especially in the transient state, that is still open problem.

Fig. 11 shows a sinusoidal response under the position control with the power-saving axial-gap displacement adjustment. The frequency of the sinusoidal reference is set to 15 Hz. The linear position of the mover and the gap displacement accurately follow the references as shown in Fig. 11 (a) and (b), respectively. The gap displacement is almost similar to the acceleration of the mover in order to balance the permanent magnet force and inertial force. In Fig. 11 (c), the d-axis current is used to change the gap displacement and the q-axis current is used to drive the motor.

C. Force Control

Fig. 12 and 13 show experimental results of the force control with and without the power-saving axial-gap displacement adjustment, respectively. A fixed tubular linear motor is provided as the load of the force control. In both cases, the measured force and estimated force follow the command value, which is 30 N, as shown in Fig. 12 (a) and Fig. 13 (a).

Under the power-saving axial-gap displacement control, the gap displacement converges to the equilibrium point -0.15 mm as shown in Fig. 12 (b), where the permanent magnet force $K_g(x_g - x_{g0})$ in (10) is balanced with the reaction force of 30 N. The d-axis current converges to zero thanks to the power-saving axial-gap displacement control as shown in Fig.

12 (c). The q-axis current remains a certain value in order to push the load.

On the other hand, without the power-saving axial-gap displacement control, the reference of the gap displacement is always constant as shown in Fig. 13 (b). Continuous d-axis current is required to generate the thrust force $K_f I_d$ in (10) that balances with the reaction force of 30 N as shown in Fig. 13 (c).

IV. CONCLUSION

In this paper, position control and force control with power-saving axial-gap displacement adjustment for the screw motor have been proposed. The equilibrium point of the magnetic attractive force between the mover magnet and the stator iron varies depending on the mover rotation angle. The experimental results show that, by the proposed controls, the axial-gap displacement is adjusted so that the d-axis current becomes almost zero even when the load force exists. The direct-drive motion has been realized by the proposed controller.

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