Analysis of Quasi-Zero Power Characteristic for a Permanent Magnetic Levitation System With a Variable Flux Path Control Mechanism

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Abstract—This article focuses on the analysis of the quasi-zero power characteristic for a permanent magnetic levitation system with a variable flux path control mechanism. The system mainly consists of a disk permanent magnet, a pair of yokes, and a rotary actuator. The permanent magnet magnetized diametrically is rotated by the actuator, which can achieve the control of the levitation force by changing the flux. Unlike the electromagnetic system, the input to the actuator is used to maintain the rotation angle corresponding to the equilibrium position, not to directly produce a magnetic force. Therefore, the proposed system possesses a lower power consumption. Analysis of mechanism, current model, and different levitation control strategies are presented in this article. With the variable air gap length control and the constant air gap length control, the permanent magnetic levitation system performs well in levitation with quasi-zero power in loading experiments. The constant air gap control is demonstrated to possess higher safety when the levitation mass is changed, which has the potential for magnetic levitation transportation.

Index Terms—Control systems, energy conservation, magnetic levitation, permanent magnets (PMs).

I. INTRODUCTION

In the manufacturing process of semiconductors, membranes, and optical lenses, the cleanliness of the dust-free environment is very important. However, traditional transportation technology cannot avoid pollution of secondary dust due to friction caused by surface contact. Maglev (magnetic levitation) technology enables contactless support. The industrial applications of maglev technology include maglev train, maglev bearing, maglev positioning platform, and maglev planar motor [1]–[5]. And the combination of magnetic levitation technology and transportation system have been proposed to improve the efficiency and cleanliness of the manufacturing process [6]–[8].

Under long-term operating conditions, the problem of high energy consumption and heat generation are important issues limiting the application of magnetic levitation technology [9]. In magnetic levitation systems, the key to reducing energy consumption is to reduce the steady-state current of the bearing control. The authors in [10]–[12] adopt optimization of structure and zero-power control method to achieve zero-power levitation.

To achieve zero power control, it is necessary to set a permanent magnet (PM) in maglev systems. As shown in Fig. 1, the levitation force is generated by the PM at the state of steady suspension. And the magnetic force generated by the electromagnetic (EM) coil only adjusts the suspended object to the equilibrium position where the gravity is offset by the permanent magnetic force [13]. When the system is levitated, the control current in the coil should be zero in theory. The zero-power control of magnetic levitation could be realized by introducing minor feedback of the current integral, minor feedback of the integral of voltage, and velocity feedback of the levitated object [14], [15]. Besides, Ueno and Higuchi [16] present a zero-power magnetic levitation technique using a composite of magnetostrictive/piezoelectric materials.

Compared with the traditional EM levitation system, the zero-power control method can reduce energy consumption. When the mass of the suspended object is changed or the external disturbance force is applied, the system will adjust to find the unique air gap length corresponding to zero-power levitation [17]. For the multipoint maglev transportation system, the air gap length at each point is different when an eccentric load is applied. And it will cause problems of tilting or losing balance.

To solve this problem, we have proposed a PM levitation system with a variable flux path control mechanism, as shown in Fig. 2. Since the reaction of the levitation force is transmitted to the base, the rotary actuator will not bear gravity load. In theory, zero power consumption levitation can be achieved [18].

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To realize quasi-zero power levitation with higher safety, this article analyzed the quasi-zero power characteristic of the permanent maglev system and proposed the constant air gap control method. At first, the relationship between the current and the equilibrium position is established. Then, we designed the double closed-loop controller for the system. Single loading experiments with variable air gap control and constant air gap control were carried out, respectively, to compare dynamic performances. At last, the quasi-zero power levitation was demonstrated with a continuous loading experiment.

II. SYSTEM DESCRIPTION

A. Principle of Variable Flux Path

The principle of the variable flux path control mechanism is shown in Fig. 2. The system consists of a disk PM, two opposite F-type permalloy cores, and a suspended ferromagnetic object. To describe the variation of flux, we assume the following. (I) The N pole has the same volume as the S pole in the diametrically magnetized PM. (II) There is no flux leakage to the air in the permanent magnetic levitation system.

Fig. 2(a) shows that the magnetic poles of the magnet are aligned in the vertical direction. In this case, the facing angle of the N pole and the S pole to each core are the same. Thus, magnetic flux comes from the N pole and is absorbed into the S pole through each core, respectively. There is no flux flowing through the suspension object, which leads to zero attractive force between the cores and the levitated object.

Fig. 2(b) shows the magnet is rotated to a certain angle and a part of magnetic flux flows through the suspended object. Consequently, the attractive force is generated between the F-type core and the levitated object. When the angle is in the range of $[90^\circ, 180^\circ]$, the amount of effective magnetic flux increases as the rotation angle increases. In the range of $[90^\circ, 180^\circ]$, the magnetic flux decreases as the angle increases. When the exceeds $180^\circ$, the magnetic flux flows in the opposite direction.

B. Prototype of the PM Levitation System

Fig. 3 shows the experimental prototype of the PM levitation system with variable flux. Two permalloy cores are installed symmetrically on the left and right sides of the PM. The annular air gap between cores and the PM could be adjusted by the 2-axis moving table 1 and 10. The PM is magnetized in the diametrical direction. The diameter of the magnet is 30 mm, while the thickness is 10 mm. The rotary actuator behind the magnet consists of a servo motor, an encoder, and a harmonic reducer. The reduction ratio of the reducer is 50, and the maximum output speed is 180 r/min. The angular acceleration is 56 rad/s$^2$. The position of the levitated object is measured by an eddy-current displacement sensor, of which the measurement range is from 0 to 10 mm and the repeatability accuracy is $10^{-5}$ mm. The initial air gap length could be changed by adjusting the 1-axis moving table.

According to the principle of virtual work, the magnetic force model is obtained by solving the partial differential of magnetic energy to the air gap. As shown in the following equation, the magnetic force is related to the rotation angle of the PM and the air gap length

$$F_m = \frac{k_m \sin^2 \theta}{(d + \Delta d_f)^2}$$

where

- $k_m$ levitation force coefficient;
- $\theta$ rotation angle of the PM;
- $d$ length of the air gap;
- $\Delta d_f$ magnetic leakage compensation for the levitation force. It depends on the structure parameters of the PM levitation system.
The finite element simulation calculation is carried out. The range of the suspension air gap is 2 to 8 mm, and the rotation angle of the magnet is 0° to 360°. In the measurement, the PM was rotated at 10° increments. Each rotation period corresponds to a fixed air gap length. Fig. 4 shows the variation of magnetic force with rotation angle by calculation results (CR) and measurement results (MR) for different air gap lengths.

The mass of suspended object \( m \) is 0.232 kg, and the air gap length at the initial equilibrium position is 5 mm. Then the displacement stiffness \( k \) is about 766 N/m, and the natural frequency of levitated part \( f \) is around 9.15 Hz as calculated in the following equation. The rotary actuator can meet the requirements of the system suspension

\[
f = \sqrt{\frac{k}{m}}/2\pi.
\]

**C. Principle of Quasi-Zero Power**

According to the levitation principle, the attractive force is generated by the magnetic flux flowing through the air gap between the permalloy cores and the suspended object. And the magnetic flux is generated by the PM driven by the rotary actuator. The gravity of the suspended object is transferred to the base through the iron core, and the actuator just drives the PM to rotate, does not support the gravitational force of the suspended object. Therefore, the PM will maintain stable levitation, and the consumption power of the actuator should be zero in principle.

However, the PM will be affected by the magnetic torque generated between the magnet and iron cores. The torque still exists in the steady suspension position, which leads to the current input to the servo motor to counteract the magnetic torque. To analyze the relationship between torque and rotational angle, the finite element calculation and measurement of magnetic torque was carried out.

The conditions set by the finite element calculation and measurement of torque are consistent with those in establishing the force model. The results of the rotational torque are shown in Fig. 5. The measurement results are consistent with the finite element CR. The magnetic torque is expressed by the following equation:

\[
T_m = \frac{k_t \sin(2\theta)}{d + \Delta d_t}
\]

where

- \( k_t \) is the torque coefficient;
- \( \Delta d_t \) is the magnetic leakage compensation for the magnetic torque.

The abovementioned analysis indicates that the magnetic torque is related to the length of the air gap and the rotation angle of the magnet. And the energy consumption of the system depends on the power of the motor. The servo controller is used to control the dc motor, which allows the current control operating mode in this PM system. The armature resistance of the motor 8.6 Ω. Therefore, the power consumption depends on the magnitude of the current.

The quasi-zero power suspension of the system can be achieved by a reasonable choice of stable suspension position including the length of the air gap and the rotation angle of the magnet. Therefore, the following analysis and experiments are all within this range.

**III. Equilibrium State Current Model**

In the PM system, the equilibrium position \((d_0, \theta_0)\) is not single. Theoretically, the levitation system needs to satisfy both the force balance of the suspended object and the torque balance of the magnet as shown as

\[
\begin{align*}
F_m (d_0, \theta_0) - mg &= 0 \\
T_m (d_0, \theta_0) + k_i i &= 0
\end{align*}
\]

where

- \( m \) is mass of the levitated object;
- \( i \) current input to the actuator;
- \( k_i \) torque coefficient of the actuator.

At the equilibrium position, the magnitude of the magnetic force is equal to the gravity of the levitated object. Substituting
(1) into the force balance equation in (4), the relationship between the equilibrium position and the levitation mass can be obtained as shown in the following equation:

\[ d_0 = \sqrt{\frac{k_m}{mg}} \sin \theta_0 - \Delta d_f. \] (5)

Then, the air gap length \( d_0 \) in the torque balance equation is eliminated by substitution of (5). Equation (6) is obtained which shows the current model relating to the rotation angle and levitation mass.

\[ i = \frac{k_m \sqrt{mg} \sin(2\theta_0)}{k_i (\sqrt{k_m} \sin \theta_0 - \sqrt{mg}(\Delta d_f + \Delta d_r))}. \] (6)

According to (5), sine of rotation angle can be expressed as

\[ \sin \theta_0 = (d_0 + \Delta d_f) \sqrt{\frac{k_m}{mg}} \] (7)

\[ \sin 2\theta_0 = 2 \sin \theta_0 \cos \theta_0. \] (8)

Then, substituting (7) and (8) into the magnetic model in (4), the current model relating to the air gap length and levitation mass is obtained as shown in the following equation:

\[ i = \frac{2mgk_m(d_0 + \Delta d_f)}{k_m k_i (d_0 + \Delta d_r)} \sqrt{\frac{k_m}{mg}} - (d_0 + \Delta d_f)^2. \] (9)

When the mass of the levitated object is constant, Fig. 6 shows changes in equilibrium position and current. Curve 1 represents the relationship between air gap length and rotation angle. When the angle of the magnet is increased, it is necessary to increase the length of the air gap as the requirement of an equilibrium condition. Similarly, when the angle of the magnet is reduced, the corresponding air gap length is also reduced. Curve 2 shows the change of current with equilibrium position. The magnitude of current input to the actuator reaches the maximum when the rotation angle is about 45°. And it will decrease as the rotation angle increases.

When the levitation mass increases, the variation of current and equilibrium position is further analyzed. When the air gap length is constant, the current is related to the mass of the levitated object and rotation angle as shown in (9). Different air gap lengths were set between 2 and 8 mm, and the current variation and maximum points are depicted in Fig. 7. The maximum point A–C are corresponding to 45° of rotation angle, as shown in Fig. 8. With a constant air gap, the rotation angle will increase as the levitation mass increases to produce enough levitation force. When the angle is less than 45°, the current also increases as the levitation increases. When it exceeds 45°, the current will decrease as the levitation mass increases.

With the same levitation mass, the variation of current in the EM levitation system and hybrid EM (HEM) levitation system is also analyzed. In [19], an HEM with a laminated soft magnetic steel core and a PM was proposed. And the magnetic force model was given out

\[ F_{HEM} = k_a \frac{(i + i_b)^2}{d^2} \] (10)

where

\[ k_a = 1.85 \times 10^{-5} \text{N} \cdot \text{m}^2 \text{A}^{-2}; \]

\[ i_b = 4.713 \text{A}; \]

\[ d = 1.3 \times 10^{-3} \text{m}. \]

Based on the same structure of HEM, an EM without the PM is also designed. It has two windings connected in series, and the total resistance is about 4.3 Ω. Each coil winding has 360 turns. The area of the magnetic pole is 2.1 \times 10^{-4} \text{m}^2. The magnetic force model is established as shown in the following equation:

\[ F_{EM} = k_b \frac{i^2}{d^2} \] (11)
With the 4 mm air gap length, the power consumption of the PM system is about 16 W, which is 5 times that of the proposed PM system. The power consumed of the proposed PM system is lower than that of the PM levitation system. But it shows a converse result when the force exceeds the above range. When the levitation force is 30 N, the power consumption of the HEM levitation system increases by about 181 W, while the permanent magnetic levitation system increases by about 3.6 W. In the range of [10 N, 20 N], the power consumption of the HEM levitation system is lower than that of the PM levitation system. But it shows a converse result when the force exceeds the above range.

When the levitation force increases by 30 N, the EM levitation system increases by about 181 W, while the permanent magnetic levitation system increases by about 3.6 W. In the range of [10 N, 20 N], the power consumption of the HEM levitation system is lower than that of the PM levitation system. But it shows a converse result when the force exceeds the above range. When the levitation force is 30 N, the power consumption of the HEM levitation system is about 16 W, which is 5 times that of the proposed PM system. The power consumption of the proposed PM system is not sensitive to changes in mass. Therefore, the PM system with variable magnetic flux has the potential for quasi-zero power levitation.

\[ P = I^2 R. \] (12)

### IV. CONTROLLER OF THE PM SYSTEM

#### A. Dynamic Model of the PM System

For the PM system, the balance requirements are shown in (4). At this point, the system is in a stable levitation position \((d_0, \theta_0)\). Since the magnetic force model and the torque model have strong nonlinearities, Taylor expansion is used for the linearization process as shown in (8) and (9).

\[
\begin{align*}
F_m(d, \theta) &\approx F_m(d_0, \theta_0) + k_{d1} \Delta d + k_{\theta1} \Delta \theta \\
k_{d1} &= \frac{\partial F_m}{\partial d} = -\frac{2k_m \sin^2 \theta_0}{(d_0 + \Delta d')^2}, \quad k_{\theta1} = \frac{\partial F_m}{\partial \theta} = \frac{k_m \sin(2\theta_0)}{(d_0 + \Delta d')^2} \\
T_m(d, \theta) &\approx T_m(d_0, \theta_0) + k_{d2} \Delta d + k_{\theta2} \Delta \theta \\
k_{d2} &= \frac{\partial T_m}{\partial d} = -\frac{k_z \sin(2\theta_0)}{(d_0 + \Delta d')^2}, \quad k_{\theta2} = \frac{\partial T_m}{\partial \theta} = \frac{2k_z \cos(2\theta_0)}{d_0 + \Delta d'}. 
\end{align*}
\] (13)

The dynamic model of the system is obtained

\[
\begin{align*}
m \ddot{d} &= c_1 \dot{d} + k_{d1} \Delta d + k_{\theta1} \Delta \theta \\
j \ddot{\theta} &= c_2 \dot{\theta} + k_{d2} \Delta d + k_{\theta2} \Delta \theta + k_i \Delta i
\end{align*}
\] (15)

where
- \(c_1\) and \(c_2\) damping coefficient of the suspended object and the actuator, respectively;
- \(k_i\) torque coefficient of the actuator;
- \(\Delta d\) change of air gap length;
- \(\Delta \theta\) rotation angle at the equilibrium position.
TABLE I
PARAMETERS OF SYSTEM

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>( J )</td>
<td>( 6.37 \times 10^4 ) kg·m²</td>
</tr>
<tr>
<td>( m )</td>
<td>0.232 kg</td>
</tr>
<tr>
<td>( g )</td>
<td>9.8 m/s²</td>
</tr>
<tr>
<td>( k_i )</td>
<td>0.69 Nm/A</td>
</tr>
<tr>
<td>( k_n )</td>
<td>1.78 ( \times 10^4 ) Nm²</td>
</tr>
<tr>
<td>( k_r )</td>
<td>-8.726 ( \times 10^6 ) Nm²</td>
</tr>
<tr>
<td>( \Delta d_t )</td>
<td>1.6 mm</td>
</tr>
<tr>
<td>( Ad_t )</td>
<td>14 mm</td>
</tr>
<tr>
<td>( c_1 )</td>
<td>-0.5 N/(m/s)</td>
</tr>
<tr>
<td>( c_2 )</td>
<td>-100 Nm/(rad/s)</td>
</tr>
</tbody>
</table>

The magnitude of other parameters is shown in Table I.

Set the state variable of the PM suspension system to \( x \), then the state space of the system can be expressed as

\[
\dot{x} = Ax + Bu + \Delta d
\]

where

\[
A = \begin{bmatrix} \Delta d & \Delta \theta & \Delta \dot{d} & \Delta \dot{\theta} \end{bmatrix}^T
\]

\[
B = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{1}{M} & 0 & \frac{1}{M} & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
\]

\[
C = \begin{bmatrix} m & 0 & 0 & 0 \\ 0 & J & 0 & 0 \\ 0 & 0 & c_1 & 0 \\ 0 & 0 & 0 & c_2 \end{bmatrix}
\]

\[
K_C = \begin{bmatrix} k_{d1} & k_{d2} \\ k_{\theta 1} & k_{\theta 2} \end{bmatrix}
\]

\[
K_I = \begin{bmatrix} 0 \end{bmatrix}
\]

B. Double Closed-Loop Controller

For magnetic levitation systems, closed-loop control is a prerequisite for stable levitation. And the air gap length is selected as the controlled variable. However, for the system proposed in this article, the levitation force is related to the rotation angle of the magnet and the air gap length. A single closed-loop controller for the air gap cannot fully reflect the state change of the system. Therefore, it is difficult to realize stable levitation.

A double closed-loop proportional-derivative (PD) controller was designed for the system. The levitation air gap is detected and feedback by the eddy-current displacement sensor and the rotation angle of the magnet is detected by an incremental encoder installed at the back of the motor. The block diagram of the system with this controller is shown in Fig. 13. And the control law is shown as

\[
u(t) = \left(K_{p1}e_d(t) + K_{d1}\frac{de_d(t)}{dt}\right) + \left(K_{p2}e_{\theta}(t) + K_{d2}\frac{de_{\theta}(t)}{dt}\right) + K_{d2}\frac{de_{\theta}(t)}{dt} + K_{i1}\int e_d(t)dt.
\]

As shown in Fig. 13, the principle of the double PD controller is the same as that of the state feedback controller, which follows the control law (18). Parameters of the state feedback controller can be obtained by the linear quadratic regulator (LQR) algorithm. Then, the parameter of the PD controller can be designed

\[
u(t) = \left(K_{p1}\Delta d + k_{d1}\Delta d\right) + \left(K_{p2}\Delta \theta + k_{\theta 1}\Delta \theta\right).
\]

According to Kalman’s controllability and observability criteria for a linear system, the PM system is controllable and observable. To obtain optimal performance of system (16) through the LQR algorithm, the following quadratic cost function should be minimized

\[
J = \frac{1}{2}\int_0^\infty [x^T(t)Qx(t) + u^T(t)Ru(t)]dt.
\]

The meaning of this performance indicator is to keep the state near zero with as little energy as possible. The Hamiltonian function of the problem is established

\[
H = \frac{1}{2}x^T(t)Qx(t) + \frac{1}{2}u^T(t)Ru(t) + \lambda^T[Ax(t) + Bu(t)]
\]

\[
u^*(t) = -R^{-1}B^T\lambda x(t) = -Kx(t).
\]

K is the state feedback gain matrix that needs to be calculated. \( P \) is the symmetric positive definite solution of the Riccati algebraic equation. The weight matrices \( Q \) and \( R \) are designed according to an analysis of state variables. Then, parameters of the PD controller could be derived based on the LQR algorithm

\[
K = \begin{bmatrix} 115778 & 112 & 297 & 0.6 \end{bmatrix}.
\]

1) Constant Air Gap Length Levitation Controller: The constant air gap controller adds an air gap integral link to the suspension controller. When the external disturbance force is loaded, the length of the air gap can be kept constant, and the stable suspension can be achieved again by changing the rotation angle. And the control law is shown as

\[
u(t) = K_{p1}e_d(t) + K_{p2}e_{\theta}(t) + K_{d1}\frac{de_d(t)}{dt} + K_{d2}\frac{de_{\theta}(t)}{dt} + K_{i1}\int e_d(t)dt.
\]
With this controller, the system current is only related to
the amount of angle change after stabilization. The system
can realize quasi-zero power suspension under the condition
of constant air gap length. The parameters of the PD controller
have been determined. The parameter gain can be determined
by system simulation to determine the integral gain as $K_{i1} = 355897$.

2) Variable Air Gap Length Controller: The variable air gap
controller adds an angle integral link to the levitation controller.
When the external disturbance force acts, the rotation angle can
be kept constant, and the stable suspension can be achieved
again by changing the air gap length. The parameter gain can be
determined by system simulation to determine the integral gain as
$K_{i2} = 8769$

$$u(t) = K_{p1}e_d(t) + K_{p2}e_\theta(t) + K_d \frac{de_d(t)}{dt} + K_{d2} \frac{de_\theta(t)}{dt}$$
$$+ K_{i2} \int e_\theta(t)dt.$$  

In this section, parameters of the double PD controller of the
system is first calculated by the LQR algorithm, and the integral
links of the air gap length and the rotation angle are introduced
to design the quasi-zero power controller.

C. Single-Load Experiment

To verify the levitation control of the PM system, experiments
with the double PD control, constant air gap control, and variable
air gap control, respectively, were carried out. The experiment
includes the process of levitating and loading. The hardware
in the control loop consists of sBOX (DSP system), LSC 30/2
(4-Q-DC Servo amplifier), and the upper PC.

According to the analysis of the current model, the reference
equilibrium position is set to $(4 \text{ mm}, 37.5^\circ)$. At first, the levitation
was achieved after enabling the controller as shown in Fig. 14.
Then, an aluminum block was put on the levitated object gently.
The mass of the aluminum block is 0.05 kg, which is about 23%
of the mass of the levitated object. And the aluminum block will
not change the magnetic flux of the system.

1) Experiment With the Double PD Controller: As shown in
Fig. 15, the stable levitation is realized after about 0.4 s. During
the levitation process, there is a 0.1 s delay in the air gap
response. The reason for the delay is that the magnetic force
in this period is less than gravity and cannot lift the suspended
object. Compared with the reference equilibrium position, the
error of the air gap is 1 mm and the error of rotation angle is
$8.5^\circ$. As a result, the steady-state current is 0.52 A, which cannot
meet the requirements of quasi-zero power levitation.

The aluminum block was loaded at 11 s, and the results of
the loading experiment are shown in Fig. 16. The air gap length
increases by 1.1 mm, and the rotation angle increases by $15.5^\circ$.
This variation of equilibrium position leads to 0.25 A reduction
of the current. It is consistent with the analysis of the steady-state
current of the system. Within a specific range of the equilibrium
position, the steady-state current will decrease as the levitation
mass increases.

2) Experiments With the Constant Air Gap Controller and the
Various Air Gap Controller: The state variables in the levitation
process are shown in Fig. 17. The variation of equilibrium position in the experiment with the variable air gap controller is
consistent with that in the experiment with the constant air gap
controller during the levitation process. As shown in the result
of the air gap, the total time to achieve levitation is about 0.33
s, which includes a 0.1 s delay. The steady-state error of the air
The air gap is 0 mm, and the error of the angle is about 0.3°. Compared with the double PD controller, the response time of the air gap is reduced by 17%, and the overshoot is reduced by 80%. Besides, the steady-state current is reduced by 69%. It indicates that the system with the proposed controller performs better in the levitation process than it with the double-PD controller.

Then, the aluminum block was loaded on the levitated object and the system would reach to new levitation state. Figs. 18 and 19 record the changes in the equilibrium position during the loading and unloading process. Fig. 20 shows the change in current input to the servomotor which can drive the PM to rotate.

With the constant air gap control, the rotation angle will increase to provide enough levitation force. And the air gap converges to the magnitude at the initial state when the weight is removed, while 0.5° error exists in the rotation angle. The overshoot of air gap length when the weight is loaded is about 50%, while when the weight is removed it is about 25%. When loading weight on the levitated object, the momentum of the weight will be transferred to the levitated object. It causes that the overshoot in loading is larger than that in unloading. The current decreases by 0.01 A and the rotation angle increases by 2° when loading the weight.

With the various air gap controller, the air gap will decrease to produce enough levitation force and the rotation angle is the same as the initial equilibrium position. In this case, the current increase by 0.04 A. When the weight is removed, the rotation angle converges to the initial state with variable air gap control. The overshoots of the air gap are both about 30% when the weight is loaded and removed. Compared with the constant air gap control method, the overshoot is 20% lower when loading the weight. However, the settling time of the variable air gap control method is 2.8 times that of the constant air gap control method when loading the weight.

As the armature resistance of the motor is 8.6 Ω, the power consumption could be calculated by (13). In the initial levitation state, the power consumption of the system is about 0.22 W. When the mass of levitated object increases by 23%, the power consumption decreases by 12% in the experiment with constant air gap controller, while it increases by 55% in the experiment with various air gap controller. In the experiment with the double PD controller, the power consumption is 2.3 W in the initial levitation process, and it decreases to 0.54 W after a 20% increase in levitation mass. Compared with the double-PD controller and various air gap controller, the proposed constant air gap controller for this permanent maglev system can realize quasi-zero power levitation without changing the air gap length at the equilibrium position.

V. QUASI-ZERO POWER CHARACTERISTIC ANALYSIS

In the experiment, the mass of the levitated object was increased from 0.12 to 1.44 kg with 0.12 kg increments. With different control methods, the equilibrium position and the power consumption corresponding to different levitation mass were recorded. And the experimental result was compared with the simulation result.

A. Quasi-Zero Power With Various Air Gap Length Control

For the PM system with various air gap control, the rotation angle was set to 40°. With the increase of levitation mass, the system will decrease the air gap length to generate greater levitation force. Therefore, the power consumption increases as the levitation increases as shown in Fig. 21. In the simulation, the power consumption is about 0.03 W when the levitation
mass is 0.12 kg. When the levitation mass increases by 11 times, the power consumption increases by 2 times. Overall, the variation trend of power in the experiment is the same as that in the simulation. The maximum power consumption is less than 0.1 W. With various air gap length control method, the power consumption of the PM system possesses a quasi-zero power characteristic.

As shown in Fig. 21, the error of power exists in experiments and simulations. And it increases as the levitation mass increases. With the same levitation mass, the air gap length in the simulation is about 0.5 mm greater than it in the experiment as shown in Fig. 22. These errors between the experiment and simulation are mainly caused by the constant compensation of the magnetic leakage. In the force model (1), $\Delta d_f$ is the leakage magnetic compensation air gap for the levitation force. And $\Delta d_T$ is the leakage magnetic compensation air gap for the magnetic torque (3). As the model of magnetic leakage is strongly nonlinear, the errors of the magnetic force increase as the air gap decreases. Besides, the levitated object is mounted on the linear guide rail as shown in Fig. 14, which leads to friction. The abovementioned two factors cause the magnetic force in the experiment is greater than that in the simulation. Therefore, the air gap must be decreased to generate enough levitation force. The levitation power in the experiment is larger than that in the simulation. Also, the measurement error is another source of this power consumption error.

B. Quasi-Zero Power With Constant Air Gap Length Control

In this simulation and experiment, the air gap length is set to 2 mm. The rotation angle is detected and fed back by the encoder. Fig. 23 shows the steady-state power consumption corresponding to different mass. Fig. 24 shows the rotation angle at the different equilibrium positions. The results indicate that the variation trend of power is the same as that in the various air gap length control. As a result of increasing the levitation mass, the rotation angle of the magnet is increased to satisfy the demand for a larger attractive force. Therefore, the power consumption increases as the levitation mass increases. When the mass increases to 1.44 kg, the corresponding rotation angle is 45°. And the power consumption of the system increases to 0.105 W. According to the current model with the rotation angle, the current will decrease as the mass increases when the angle exceeds 45°.

The errors between the simulation and the experiment were investigated. The simplification of magnetic leakage in the magnetic force model and magnetic model is the main reason for this problem. As shown in Fig. 23, the rotation angle in the experiment is smaller than that in simulation. However, the magnetic torque in experiment measurement is larger than that in simulation, which causes a higher power consumption in the levitation experiment. Moreover, the effect of friction and the random error in measurement also cause errors in power consumption results.

According to continuous loading experiments, the PM levitation system with variable flux could achieve levitation with quasi-zero power has been demonstrated. The constant air gap control and the variable air gap control perform similarly in terms of power consumption. However, the variation of equilibrium position is different in the process of continuous loading. With the constant air gap control method, the system has the potential to be applied to four-point magnetic levitation transportation, which can avoid the problem of platform tilting when loading eccentric loads.
VI. CONCLUSION

In this article, the quasi-zero characteristic of the PM levitation system with variable flux is analyzed and successfully demonstrated by levitation experiments. The power consumption was evaluated by the current input to the actuator, which is related to the equilibrium position. Compared with the double PD controller, the constant air gap control method and variable air gap control method have a shorter response and smaller steady-state error. The two controllers proposed in this article perform similarly in terms of power consumption. However, the system with constant air gap control could maintain the air gap constant, which ensures the safety of the system when the levitated mass is changed. Therefore, the PM system with the constant air gap controller has greater potential for transportation.

Future works include improving the mechanism and optimizing the controller to enhance the dynamic performance to reduce the overshoots of the air gap. And the dynamic performance capability of the system would be further investigated to confirm the range of disturbance frequency according to requirements of clean transportation application. Based on the abovementioned research, a four-point PM levitation conveyor with quasi-zero power will be developed.

REFERENCES


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