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Lateral air-gap control of a novel detent-force-based Magnetic Suspension System

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Abstract: To solve the possible lateral displacement caused by external disturbance forces in the novel Detent-force-based Magnetic Suspension System (DMSS), the lateral air gap control system with a differential control strategy of dual-electromagnet is studied. A dual-electromagnet model with a lateral air gap control system is established, and a fuzzy PID controller is designed based on fuzzy control theory, realizing online self-tuning of the PID parameters. The simulation result shows that the fuzzy PID controller has better dynamic and anti-jamming performance. It provides an important theoretical basis for the application of the lateral air gap control system in the actual magnetic levitation systems.

Keywords: Magnetic suspension; Detent force; The lateral air gap control; Fuzzy-PID.

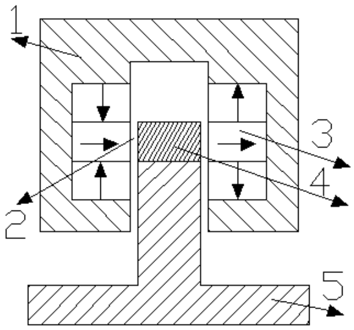
1. Introduction

The principle of minimum magnetic reluctance to achieve passive levitation in one or multiple degrees of freedom has been widely adopted in several magnetic levitation systems due to simple structure and low cost, such as the Bearingless Slice Motor, the Medium- or Low-Speed Magnetic levitation Train CMS03A, and the GA Magnetic levitation Vehicle, etc[1-3]. A novel Detent-force-based Magnetic Suspension System (DMSS) is proposed, working based on the principle of minimum magnetic reluctance in the axial direction. It has advantages of high levitation force, low energy consumption, and low loss, and has wide application prospects in magnetic levitation platforms, magnetic levitation trains, and vibration dampers, etc. During the levitation process, the influence of various disturbing forces may cause lateral displacement of the suspended body, while the lateral attractive force increases with the increase in lateral displacement, therefore, the control of the air gap is necessary. In this paper, the lateral air gap control system with dual-electromagnet differential control is studied. A mathematical model of the lateral air gap control system is established, and a fuzzy PID controller is designed to achieve online self-tuning of PID parameters.

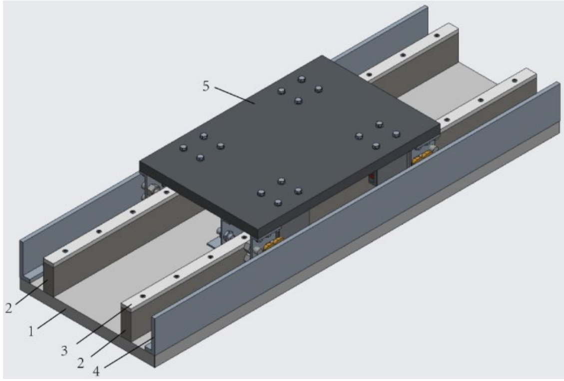
2. A novel Detent-force-based Magnetic Suspension System (DMSS)

The structure of the novel Detent-force-based Magnetic Suspension System (DMSS) is shown in Fig. 1. Two parallel Halbach permanent magnet (PM) arrays with the same height are fixed on the inner surface of the inverted U-shaped magnets brace. The magnetization directions of the permanent magnets are shown with the arrows in Fig. 1. There is a yoke between the two arrays, which is supported by a non-magnetic yoke brace to form the rail. Meanwhile, two wheels are installed on the two sides of sytem to ensure the system operating within a safe range.

The system has several advantages below. 1) The strong magnetic field generated by the Halbach array forms magnetic flux loops on the inside, enhancing the magnetic flux density in the air gap. It can achieve a levitation force at least one order of magnitude greater than that of ordinary magnets, and it can also prevent PM from attracting external magnetic debris. 2) The rail consists solely of non-magnetic yoke brace and iron yoke, eliminating the need for permanent magnets and preventing high-temperature demagnetization. It will greatly reduce rail costs and resolve the magnetic shielding issues associated with permanent magnet rail. Therefore, this system holds broad application prospects in areas such as levitation workbenches, magnetic levitation trains, and device vibration damping.



1) Magnets brace 2) Air-gap 3) Halbach permanent magnets array 4) Iron yoke 5) Non-magnetic yoke brace



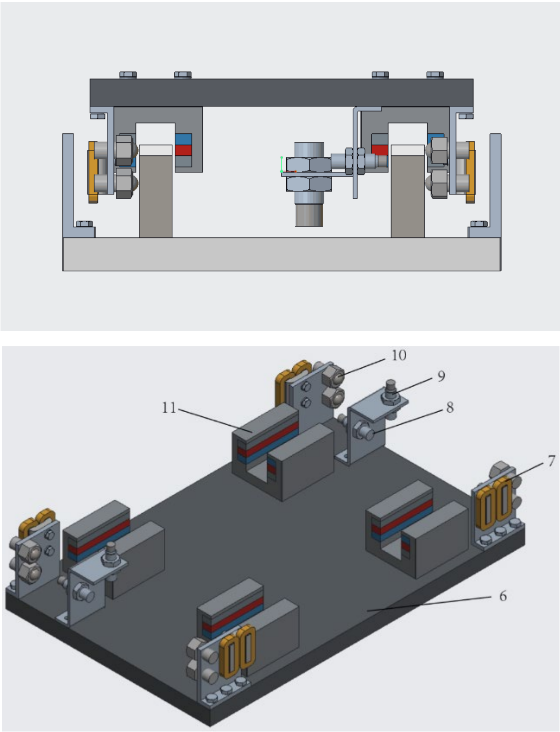


Fig. 1 The structure of Detent-force-based Magnetic Suspension System (DMSS)

3. The model of the lateral air gap control system

The passive levitation is achieved in the axial direction of the DMMS based on the principle of minimum magnetic reluctance. Thus, it has the capability of self-corrections in the axial direction. Be analogous to the spring, the lateral attractive force and lateral displacement are approximately linear. When lateral force and lateral displacement exhibit an approximate linear relationship, greater lateral displacement results in greater lateral force. The levitated object tends to continue shifting and it is necessary to be controlled.

Due to the close correlation between lateral attractive force and factors such as the position of the levitated body, system structure, and magnetic leakage, it is difficult to build the mathematical model for the lateral attractive force. In the model, it is treated as a disturbance. Fig. 2 shows the simplified structure of the single-point control system for a dual-electromagnet rail.

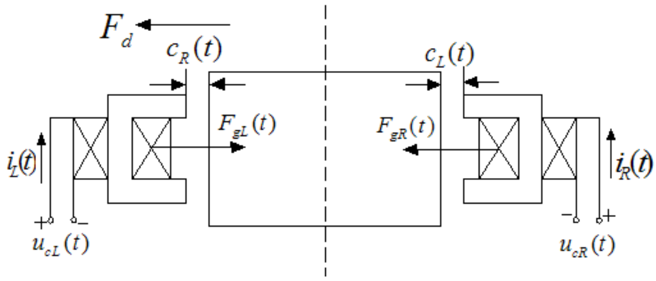


Fig. 2 The structure of the lateral air-gap control system

In Fig. 2, cL(t) and cR(t) are the left and right air gaps between the two electromagnets and the rail, respectively. ucL(t) and ucR(t) are the control voltages of the two electromagnets, respectively. iL(t) and iR(t) are the currents of the two electromagnets, respectively. FgL(t) and FgR(t) are the electromagnetic forces of the two electromagnets, respectively. Fd is the external disturbing force in the lateral direction on the system. The levitated body is treated as a rigid body, and the lateral deformation of the rail is ignored.

In the equilibrium position (both the left and right air gaps are c0), the currents are also the same, and the values of right and left electromagnetic forces are the same, while the directions are opposite. If subjected to a lateral disturbance force Fd at time t, the system will deviate from its equilibrium position (let the displacement be Δc). The air gap sensor detects the air gap displacement, and the controller converts this displacement signal into a control signal. The power amplifier converts the control signal into an electrical current, increasing the current in the electromagnet on the side where the gap is widening and decreasing the current in the electromagnet on the side where the gap is narrowing. This generates a restoring force that returns the suspended body to its equilibrium position, at which point the system operates as a dual-electromagnet control system. When the lateral interference force exceeds a certain threshold, |Δi|>i0 is present, causing the current in one side of the electromagnet to drop to zero. At this point, only one electromagnet is active, and the lateral system operates as a single-electromagnet control system.

The lateral air gap control system mainly works as a dual-electromagnet system, so a dual-electromagnet differential model is used to design the controller. At the equilibrium position, cL(t)= cR(t)= c0, iL(t)= iR(t)= i0, ucL(t)= uRL (t)= u0. After linearization at the equilibrium position, the system model of the left electromagnet is expressed as equation (1).

$$\begin{cases} m\Delta\ddot{c} = 2k_c\Delta c - 2k_i\Delta i + \Delta F_d \\ \Delta u = R\Delta i + L_0\Delta\dot{i} - k_i\Delta\dot{c} \\ k_c = F_c(i_0, c_0) = \dfrac{\mu_0 A N^2 {i_0}^2}{2{c_0}^3} \\ k_i = F_i(i_0, c_0) = \dfrac{\mu_0 A N^2 i_0}{2{c_0}^2} \\ L_0 = \dfrac{\mu_0 A N^2}{2c_0} \\ L_0 k_c = {k_i}^2 \end{cases} \tag{1}$$

In equation (1), μ0, m, A, N, and R denote the vacuum permeability, the mass, the area of the electromagnet, the number of turns, and the resistance, respectively. kc and ki are the air gap coefficient and current coefficient, respectively. L0 denotes the inductance at the equilibrium position.

$x = [\Delta c \quad \Delta\dot{c}]^T$ is selected as the state variable, (Selecting $x = [\Delta c \quad \Delta\dot{c}]^T$ as the state variable,) the state space model with the electrical current as the input variable is expressed as equation (2).

$$\begin{aligned} \begin{bmatrix} \Delta\dot{c} \\ \Delta\ddot{c} \end{bmatrix} &= \begin{bmatrix} 0 & 1 \\ 2\dfrac{k_c}{m} & 0 \end{bmatrix} \cdot \begin{bmatrix} \Delta c \\ \Delta\dot{c} \end{bmatrix} + \begin{bmatrix} 0 \\ -2\dfrac{k_i}{m} \end{bmatrix} \cdot \Delta i \\ y &= \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{bmatrix} \Delta c \\ \Delta\dot{c} \end{bmatrix} \end{aligned} \tag{2}$$

To achieve steady-state positional accuracy without static error, a new state variable $\int \Delta c dt$ is introduced, and the control law $\Delta i = k_I \int \Delta c dt + k_P \Delta c + k_D \Delta \dot{c}$ is applied. Then, a closed-loop system for the state-space model is obtained and expressed as equation (3).

$$\begin{bmatrix} \Delta c \\ \Delta \dot{c} \\ \Delta \ddot{c} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -k_I \dfrac{2k_i}{m} & \dfrac{2k_c}{m} - k_P \dfrac{2k_i}{m} & -k_D \dfrac{2k_i}{m} \end{bmatrix} \cdot \begin{bmatrix} \int \Delta c dt \\ \Delta c \\ \Delta \dot{c} \end{bmatrix} \quad (3)$$

$$y = \begin{pmatrix} 0 & 1 & 0 \end{pmatrix} \begin{bmatrix} \int \Delta c dt \\ \Delta c \\ \Delta \dot{c} \end{bmatrix}$$

4. 3 The design of the Fuzzy PID Controller

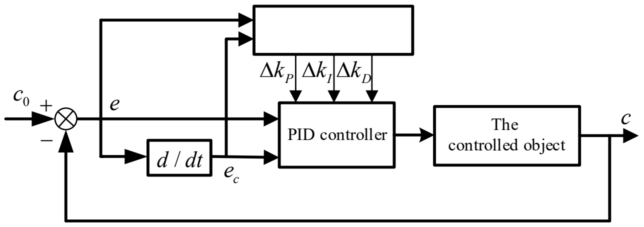


Fig.3 The diagram of the Fuzzy Adaptive PID Control System

A typical diagram of the fuzzy adaptive PID control system is shown in Fig. 3, including a conventional PID controller and a fuzzy controller. The deviation e and the change rate of deviation ec are used as input variables. Three PID parameters of kp, kI, and kD are corrected online through fuzzy control rules to meet the requirements of e and ec for PID parameter self-tuning at different times.

In the lateral air gap control system, the deviation e and the change rate of deviation ec are input variables. The key to designing a fuzzy control system is to identify the fuzzy relationships between the parameters of kP, kI, kD and e, ec. The overshoot should be reduced, the response speed should be increased, and the stability should also be enhanced. Therefore, based on the previous experiences, the initial fuzzy rule table is established. The fuzzy rule table of parameter kP is listed in Table 1.

Table 1. The fuzzy rule table of kp

E	Ec						
	NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	PB	PB	PM	PM	PS	ZE	ZE
NM	PB	PB	PM	PS	PS	ZE	NS
NS	PM	PM	PM	PS	ZE	NS	NS
ZE	PM	PM	PS	ZE	NS	NM	NM
PS	PS	PS	ZE	NS	NS	NM	NM
PM	PS	ZE	NS	NM	NM	NM	NB
PB	ZE	ZE	NM	NM	NM	NB	NB

The air gaps of both sides are 2mm at the equilibrium position. The base universes of discourse for deviation e and ec are set as [-0.5, 0.5]mm and [-0.1, 0.1]m/s, respectively. The quantized universes of discourse for e and ec are both set as (-5, 5), and divided into 7 levels. The fuzzy subsets are {NB, NM, NS, ZE, PS, PM, PB}, meaning negative large, negative medium, negative small, zero, positive small, positive medium, and positive large, respectively. Similarly, the fuzzy subsets of the quantized universes of discourse for the output variables kP, kI and kD are also set as {NB, NM, NS, ZE, PS, PM, PB}. The corresponding proportional factors are set according to fundamental principles and experiences. Considering that the lateral air gap control system should exhibit finer movement near the equilibrium position, the fuzzy subsets are unevenly partitioned over the domain. The input-output relationship curves are shown in Fig. 4.

The Mandani algorithm is used for fuzzy inference, and the Center of Gravity (CoG) Method is used for defuzzification.

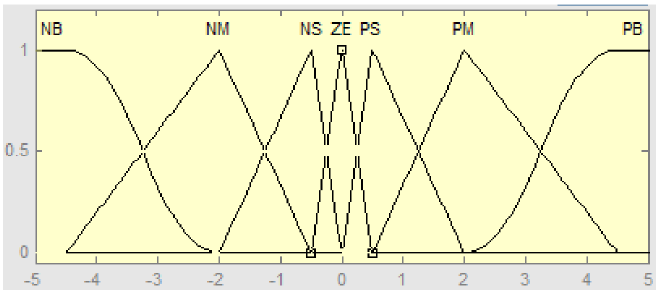


Fig.4 The membership functions of inputs and outputs

5. The simulation of the Fuzzy PID Controller

In simulation, the area of the lateral control electromagnet pole is set as A=450mm2, the number of turns is set as N=250, the resistor is set as $R = 0.7\Omega$, the mass of the levitated body is set as m=60kg, the steady bias current is set as 7A, and the air gap at equilibrium position is set as 2mm.

According to the above parameters, the equilibrium position is calculated as kc=108240, ki=30.9251, and Lo=0.0088. Using the method of pole placement, the conventional PID parameters are determined as kD=3492.3, kP=1932600, kI=548860000. Due to the robustness of PID control and the flexibility of fuzzy controllers, the adjustment of PID parameters is not highly dependent on the precision of initial values. Therefore, the initial values of the parameters kD, kP, and kI for the conventional PID control are used in this case.

At the time of 0s, a static disturbing force of 200N is applied on the lateral air gap control system, the simulation is performed with MATLAB/Simulink toolbox. The curves of the deviations of air gap obtained from conventional PID and fuzzy PID are shown in Fig. 5, and the variations of electrical current in the electromagnet obtained from fuzzy PID are shown in Fig. 6.

To reduce steady-state error, both the conventional PID and fuzzy PID controllers include integral feedback of the air gap. The simulation results show that the lateral stability of the system can be achieved in both the conventional PID and the fuzzy PID, but the latter exhibits smaller overshoot and a more rapid response, the adjustment time is obviously shorter, the steady-state accuracy is higher, and stronger robustness.

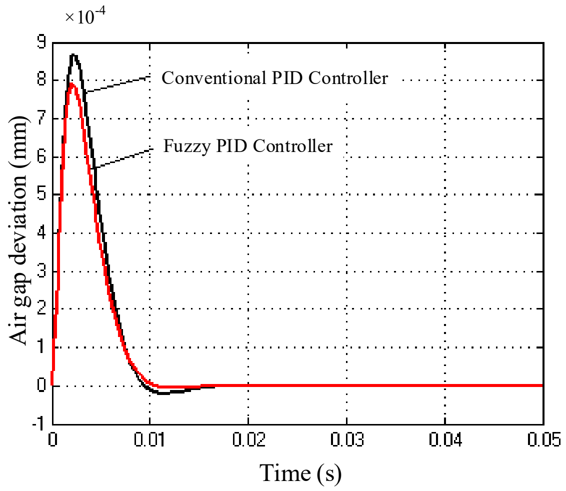


Fig.5 The deviations of air gap obtained from conventional PID and fuzzy PID

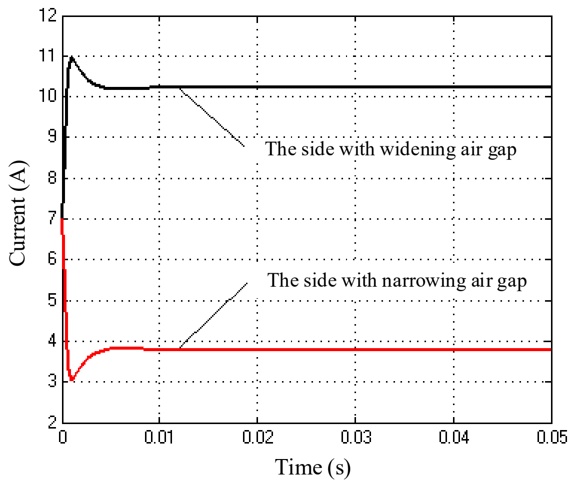


Fig.6 The variations of electrical current in the electromagnet obtained from fuzzy PID

6. Conclusion

Aiming at the lateral magnetic attractive force increasing with the increase of lateral displacement of the Detent-force-based Magnetic Suspension System (DMSS), the lateral air gap control system is designed using an electromagnet differential control method. In this paper, a mathematical model of the dual-electromagnet system is built first, and then the fuzzy PID controller is designed. The simulation results show that the fuzzy PID controller has better dynamics and the capacity of resisting disturbance. This work provides the theoretical fundamentals for the future applications of hybrid magnetic levitation system controllers in practical magnetic levitation devices.

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