Control Simulation of Active Magnetic Levitation  
Closed-loop PID System  
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Abstract. To realize “starting breeze, breeze power”, using electromagnetic force to adjust the displacement of the magnetic suspension rotor of the wind turbine. Through the force analysis, the equation of motion of the magnetic suspension rotor is established. Closed loop PID control system is designed to obtain the transfer function of the closed loop system, according to the characteristic equation to determine the range of PID parameters, and then through the MATLAB Simulink simulation gives the specific PID parameters of the stable suspension. In order to lay a theoretical foundation for the stability control of magnetic levitation, a feasible method is provided for finding the PID parameters.

Active Magnetic Levitation Force Analysis

The rotor is suspended by the magnetic suspension supporting technology, the smaller the current power consumption of the suspended rotor, and the more significant the magnetic levitation wind power generation, in this structure, the permanent magnet is used to establish the bias magnetic field [1-3], and then the electromagnetic force is used to adjust the dynamic balance. Four-tooth structure is adopted for magnetic suspension support, 4 coils are wound on the stator, the rotor has 4 convex tooth cores, and the radial displacement of the magnetic suspension rotor is changed by electromagnetic force.

Ignoring the magnetic flux leakage and the core reluctance, when the current of a single coil is current, the electromagnetic field distribution is shown in Fig. 1, due to non-uniform distribution or magnetic flux density is not uniform, so in the vertical direction of electromagnetic attraction and movement, the expression of its electromagnetic attraction is\textsuperscript{[4,5]}:

\[ F = \frac{B^2A_s}{2\mu_0} = \frac{\mu_0N^2I^2A_s}{8x^2}. \]  

Where, \(B\) is air gap magnetic induction strength, \(A_s\) is air gap cross section area, \(\mu_0\) is magnetic space constant, \(N\) is winding turns, \(I\) is control current, \(x\) is displacement of air gap.

Assuming that the mass of the magnetic suspension rotor is \(m\), its gravity has been offset by the permanent magnetic structure, which can be regarded as an ideal moving medium, the
definition of the static bias current, the balance of the rotor displacement, the equations of
motion of the magnetic suspension rotor are established by using Newton's law, and the
Taylor's formula is adopted at the equilibrium point, ignoring higher-order terms is:

\[
F = \frac{B^2A_s}{2\mu_0} = \frac{\mu_0 N^2 I_0^2 A_s}{8x^2}. \tag{2}
\]

Where, \( k_x = -\frac{4\mu_0 N^2 I_0^2 A_s}{8x_0^3} \) is displacement stiffness coefficient, \( k_i = \frac{4\mu_0 N^2 I_0 A_s}{8x_0^2} \) is current
stiffness coefficient.

![Magnetic field distribution diagram](image1)

![Distribution map of magnetic flux density](image2)

**Figure 1. Distribution of electromagnetic field in single coil.**

**PID Controller Parameter Range**

The transfer function of the PID regulator is:

\[
\frac{U(s)}{E(s)} = k_p + k_i \frac{s}{1 + k_d s}. \tag{3}
\]

Where, \( k_p \) is ratio coefficient, \( k_i \) is integral coefficient, \( k_d \) is differential coefficient.

By the Equ.2, the open-loop transfer function of the magnetic suspension rotor was
calculated by the Laplace transformation is:

\[
\frac{X(s)}{I(s)} = -\frac{k_i}{ms^2 + k_x}. \tag{4}
\]

For the simulation of single coil power supply as much as possible, the static bias current
value should approach zero, values of other parameters as shown in Table 1.
Table 1. Parameter table.

| Symbol | Value   | Unit   | Description               |
|--------|---------|--------|---------------------------|
| $I_0$  | 0.0001  | A      | Static bias current       |
| $x_0$  | $0.5 \times 10^{-3}$ | m | Balance position rotor   |
| $N$    | 200     |        | Turn Ratio displacement  |
| $A_s$  | $300 \times 10^{-6}$ | m² | Cross section area of iron core |
| $m$    | 3       | Kg     | Rotor mass                |
| $k_a$  | 1.0     | A/V    | Power amplifier gain      |
| $k_s$  | 300     | V/m    | Sensor feedback gain      |

Figure 2. Simulation of magnetic levitation control system.

The transfer function of the closed-loop system corresponding to the Fig. 2 is as following:

$$G(s) = \frac{-0.0010(k_ds^2+k_ps+k_l)}{s^3-0.3016k_ds^2-(0.3016k_p+0.0002)s-0.3016k_l}. \quad (5)$$

Based on the system characteristic equation of the closed-loop transfer function, write the ROUTH criterion table [6], as shown in Table 2.

Table 2. the ROUTH criterion table.

|      | s³ |     | s² |     | s¹ |     | s⁰ |
|------|----|-----|----|-----|----|-----|----|
|      | I  |     | $-0.3016k_d$ |     | $-0.3016k_l$ |     | $-(0.3016k_p+0.0002)$ |     |
|      |    |     | $-0.3016k_l$ |     |               |     | $-(0.3016k_p+0.0002)$ |     |
|      |    |     |               |     |               |     | $-(0.3016k_p+0.0002)$ |     |
|      |    |     |               |     |               |     | $-0.3016k_l$ |     |

When the control system is stable, the range of PID parameters is as following:

$$\begin{cases} 
    k_p < -\frac{k_l}{0.3016k_d} - 0.0007 \\
    k_l < 0 \\
    k_d < 0 
\end{cases} \quad (6)$$

Control System MATLAB Simulation

According to Table 1 parameter values, based on the Simulink MATLAB environment to establish the magnetic levitation control system simulation structure, as shown in Fig.2.
Matlab built-in PID controller module is closely linked to sampling time and filtration coefficient, which is different from the program codes that run with DSP (digital signal processor) processor of the distinction, therefore writing PID algorithm which corresponds to the Equ.3 by the C language S-function template, and in the simulation environment to customize the S-Function function call[7,8].

As a group of unstable PID parameters, the response of the system is shown in Fig.3, and the visible curve is divergent. Due to overshoot, settling time, steady state error and other factors, not all of the PID parameters which satisfy the stability control conditions are available, after repeated tests, a set of stable PID parameters is obtained, and the response of the system is shown in Fig.4, the visible system is stable at the equilibrium position within the 1s that air gap spacing is 0.5mm, steady state error and control effect basically meets the requirements, But at this time the value of the PID parameter is very large, this is because the value of the bias current is small, which leads to the small displacement stiffness coefficient and the small current stiffness coefficient, the stable response of the system needs to be high enough to be able to adjust the magnetic suspension rotor to the balance position, which have put forward higher requirements to the response time of the control circuit, the ability to withstand voltage, over current capacity, and so on.

![Figure 3. Unstable response curve.](image1)
![Figure 4. Stability response curve.](image2)

**Summary**

The magnetic levitation system is a stable system of closed loop feedback control, the equations of motion of the rotor are obtained by the force analysis, and the PID control parameters are obtained by the characteristic root of the transfer function of the closed loop system, through the Simulink MATLAB function, we give the specific PID parameter value of the stable magnetic levitation, which solves the problem that the field can only modify the PID parameters by experience, saving time and improving the efficiency. The simulation shows that the static bias current can also be used to achieve the stable suspension of the magnetic suspension rotor, which can further improve the energy efficiency of wind power generation.
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