Variable Structure Control for Active Magnetic Bearings

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Abstract: A novel flux control model is proposed in this paper, accomplished by variable structure control. The actuator designed is linear in full operation range, and has a good dynamic response. The power stage is simple, and can be designed to decrease static power loss.

Introduction

In the process of AMB-actuator design, the output variables are forces, however the input variables can be chosen from current, voltage, or flux density [1]. Up to now, the design of current control actuators is achieved by linearization of force at a given operating point, combined with **PD/PID** controllers [2]. However, systems configured in this way are very sensitive to the system parameters, for example the operating point, so robustness of the systems is not always satisfactory. Voltage control actuators are mainly used in digital systems, which have a high order system model, and can also be used in sensorless control applications [3]. The high speed Digital Signal Processors (DSP) enable nonlinear controllers to be realized, such as sliding mode control [4] and fuzzy control etc. A new kind of variable structure con-trol scheme based on flux density model is put forward in this paper, and the scheme results a very simple actuator that can be easily accomplished by DSP. The actuator is linearized in full operation range, so has value in variable operating point application. Simulation results show the feasibility of the proposed actuator scheme.

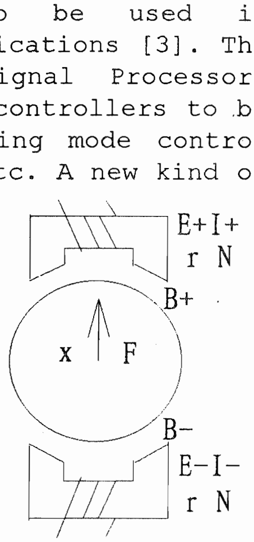

Figure 1.

Flux Control Model

Here a flux control model accomplished by variable structure control is derived for a single DOF AMB system. The typical single DOF magnetic bearing is shown in figure 1. The magnetic force can be expressed as:

$$\mathbf{F}_\Sigma = \mathbf{F}_+ + \mathbf{F}_- = \frac{\mathbf{A}}{\mu_0}(\mathbf{B}_+^2 - \mathbf{B}_-^2) \tag{1-1}$$

$$\textbf{where}\quad \mathbf{B}_+ = \frac{\mu_0 \mathbf{N}\mathbf{I}_+}{2(\mathbf{X}_0 - \mathbf{X})} \qquad \mathbf{B}_- = \frac{\mu_0 \mathbf{N}\mathbf{I}_-}{2(\mathbf{X}_0 + \mathbf{X})} \tag{1-2}$$

The relation of coil terminal voltage can be found as:

$$\begin{aligned} &\mathbf{NA}\dot{\mathbf{B}}_+ + \mathbf{r}\mathbf{I}_+ = \mathbf{E}_+ \\ &\mathbf{NA}\dot{\mathbf{B}}_- + \mathbf{r}\mathbf{I}_- = \mathbf{E}_- \end{aligned} \tag{1-3}$$

Substituting current in equation(1-3) with equation (1-2), and introducing the notes

$$\begin{aligned} &\mathbf{B}_a = \mathbf{B}_+ + \mathbf{B}_-, \\ &\mathbf{B}_s = \mathbf{B}_+ - \mathbf{B}_- \end{aligned} \tag{1-4}$$

B+ and **B-** can be converted to **Ba** and **Bs** by equation (1-4) as (1-5)

$$\begin{aligned} &\mathbf{F}_\Sigma = \frac{\mathbf{A}}{\mu_0}\mathbf{B}_a\mathbf{B}_s \\ &\dot{\mathbf{B}}_a + \frac{\mathbf{B}_a}{\mathbf{T}_L} - \frac{\mathbf{B}_s}{\mathbf{T}_L}\mathbf{x} = \alpha(\mathbf{E}_+ + \mathbf{E}_-) \equiv \mathbf{U}_a \\ &\dot{\mathbf{B}}_s + \frac{\mathbf{B}_s}{\mathbf{T}_L} - \frac{\mathbf{B}_a}{\mathbf{T}_L}\mathbf{x} = \alpha(\mathbf{E}_+ - \mathbf{E}_-) \equiv \mathbf{U}_s \end{aligned} \tag{1-5}$$

Where **x** has a unit of X_0, the standard air gap, i.e. $x=X/X_0$ and

$$\frac{1}{T_L}=\frac{2rX_0}{\mu_0 N^2 A}, \qquad \alpha=\frac{1}{NA} \tag{1-6}$$

As known later, the equivalent voltage of **Ua** and **Us** can be controlled separately, so do **Ba** and **Bs**. For simplicity **Ba** is made approximately constant as a bias flux, and **Bs** is controlled to follow the expect force signal. **Ba** can be regarded as bias flux equivalent to bias current in current model. The quantity of **Ba** is restrained by magnetic materials. So, the magnetic force is linear to control signal **Bs**. Consider $B_a \approx B_a^* = \mathbf{const}.$ motion equation of rotor can be obtained as

$$(MX_0)\ddot{x} \approx \left(\frac{A}{\mu_0}B_a^*\right)B_s + f_L$$

$$\dot{B}_s + \frac{B_s}{T_L} - \frac{B_a^*}{T_L}x \approx U_s \tag{1-7}$$

Where f_L is the load force, by selection **PD** control reference of $B_s^* = -K_P x - K_d\dot{x}$, (or **PID**, state variable feedback, direct design of sliding mode surface),the linear system above is stable and simple.

Variable structure actuator

1. Main controller design

Bang-bang control is a kind of sliding mode control with very simple sliding surface. Ignore the resistance of the coil, we get $\dot{B}_a = U_a$ $\dot{B}_s = U_s$, so the variable structure control law can be chosen as

$$\begin{cases} U_a = -E_C \bullet \operatorname{sgn}(B_a - B_a^*) \\ U_s = -E_C \bullet \operatorname{sgn}(B_s - B_s^*) \end{cases} \Rightarrow \begin{cases} (\dot{B}_a - B_a^*) \bullet (B_a - B_a^*) \le 0 \\ (\dot{B}_s - B_s^*) \bullet (B_s - B_s^*) \le 0 \end{cases} \tag{1-8}$$

From Utkin's equivalent control concepts [5], the control scheme can be regarded as an average voltage control of **Ua** and **Us** by switch amplifier. By design proper supply voltage, the whole phase plane can be attractive region. To accomplish the proposed object requires the flux control input of **Ua** and **Us** large enough compared with terms except derivative term in second and third equation of (1-5). In fact these terms caused by the voltage on the coil resistance, are usually very small. The error of control will be restrained to a small region near zero varying at a very high switch frequency (for example 20KHz). Figure 2. shows the configuration of the flux controller.

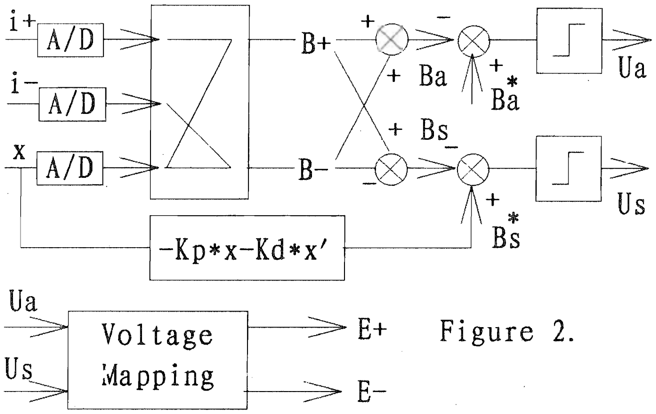

Figure 2.

By sampling current and displacement, flux is calculated by equation (1-2). Hall effect sensors for directly measuring flux can also be used, which results a high performance but also high cost. After getting **Ba** and **Bs**, by comparing with reference signal the switch signals for **Ua** and **Us** are generated, then they are mapped to upper and lower magnetic coil voltages.

2. Power Amplifier design

Voltage mapping method was formerly used in field oriented control of induction motor by I.TAKAHASHI [6]. Consider an H bridge drive stage in figure 3. The bridge has four states by selecting [T1, T2] from one of the four states [0,0] [0,1] [1,0] [1,1]. Ignore the resistance of coil and voltage drop on power switches, the voltages of coil are -Ec, 0, 0, Ec, respectively. The states [0,1] [1,0] are not used in normally current amplifiers,

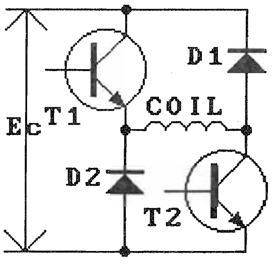

Figure 3.

but have a great value in this application.

Considering both coil, there are nine different voltage combinations of **Ua** and **Us**, as shown in table 1. Desired voltage required by equation (1-8) can be selected from one of states (2) (4) (6) (8).

By deliberate designed software, the other states can be used either to follow large reference signal or to optimize switch frequency. States(1) (9) can be used at start process to accelerate the setup of bias flux. States (3) (7) can be used when there is a large force reference. States (5) can be add when the system is at steady states, to decrease the switch frequency, thus decrease the power dissipation.

	E_+	E_-	$E_+ + E_-$	$E_+ - E_-$
(1)	Ec	Ec	2Ec	0
(2)	Ec	0	Ec	Ec
(3)	Ec	-Ec	0	2Ec
(4)	0	Ec	Ec	-Ec
(5)	0	0	0	0
(6)	0	-Ec	-Ec	Ec
(7)	-Ec	Ec	0	-2Ec
(8)	-Ec	0	-Ec	-Ec
(9)	-Ec	-Ec	-2Ec	0

Table 1

3. Advantage of the scheme

The control model is not sensitive to operating point, so the operating point can be changed in some applications to decrease the power consumption. For example, move the AMB rotor closer to magnet that has a larger attract force, the total power used will decrease.

Assume the force is the same, so

$$B_+ = B_a^*(1+k)/2 \qquad B_- = B_a^*(1-k)/2 \qquad k<1$$
$$I_+ \propto B_+(1-x) \qquad I_- \propto B_-(1+x) \qquad (1\text{-}9)$$

The power loss is proportion to $I_+^2 + I_-^2$,

$$P_{loss} \propto (1+k)^2 \bullet (1-x)^2 + (1-k)^2 \bullet (1+x)^2 \qquad (1\text{-}10)$$

When $x = \frac{2k}{1+k^2}$ the power loss is minimal. However for safe operation the point can not move too close to the boarder.

Beside that the bias flux can be controlled dynamically, so proper bias flux can be selected in accordance with the load status. When the load is light, the bias flux can be decreased, at the same time adjust the gain of controller to maintain same close loop gain. By this way the power dissipation will decrease with light loads.

Simulation results

Simulation results are enclosed, which come from solving equation (1-5) by ODE method. System parameters used are: Ec= 50v, N=130, r=.3ohm, A=5.5e-4, x_0=3e-4, M=2.175Kg.

Figure 4. and figure 5. show that the start up process is complete in 5ms.

Figure 6. and figure 7. show the response of rotor when suddenly getting a velocity of 0.6 x_0/ms.

Figure 8. shows the step response of x with different load force. Figure 9. shows more clearly of the step response with 200N load force.

Conclusion

1. Variable structure control proposed in this paper are linear in a large operation range which benefit from the flux model and control of the upper and lower magnetic coil voltages agreeably.
2. Simulation results show that the system proposed has a high performance in start, great changes in load, and impulse of momentum.
3. The flux model can monitor the flux density in each magnet, thus has the advantage of using magnetic material effectively.
4. The control scheme has a built-in switch amplifier in DSP, which simplifies the design of system hardware.
5. The scheme can be applied to 5 DOF system except the equation of motion is different.
6. The consecutive experiment is in preparation.

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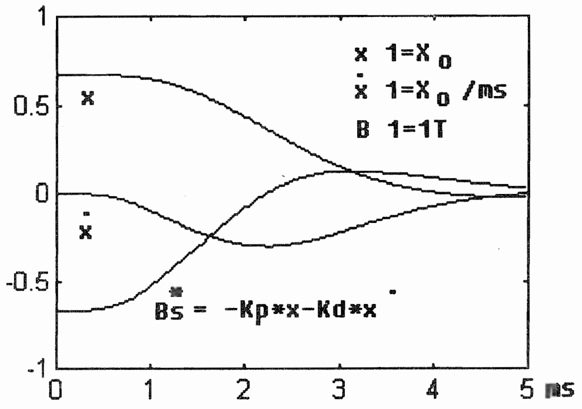

Figure 4.

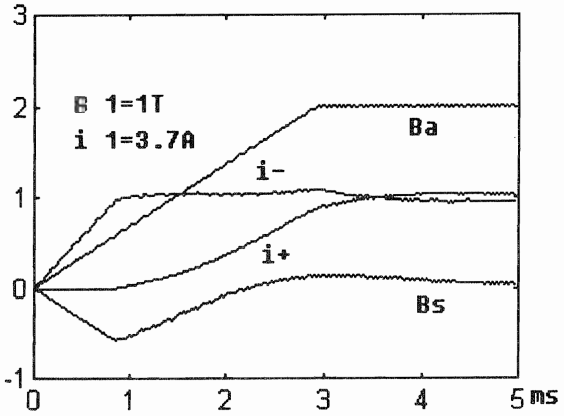

Figure 5.

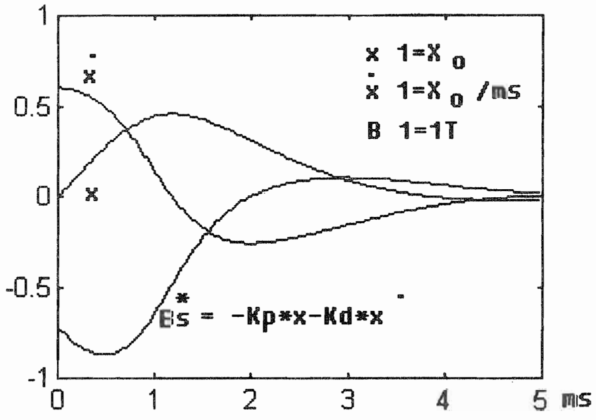

Figure 6.

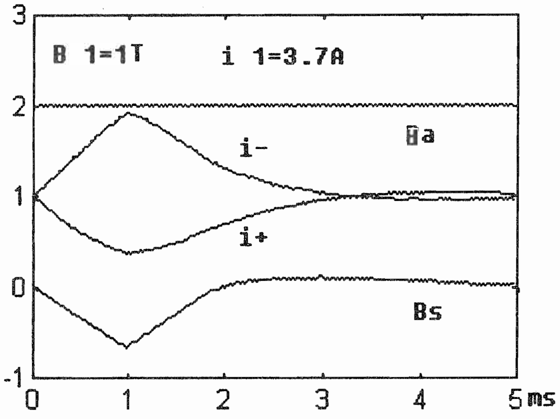

Figure 7.

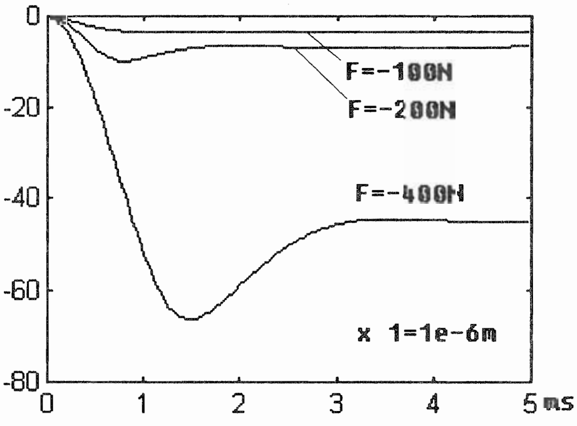

Figure 8. x-t

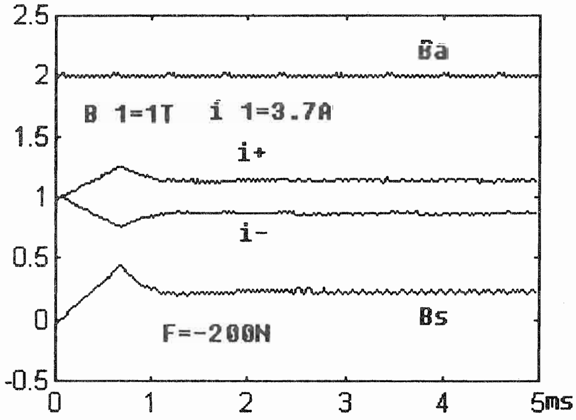

Figure 9.

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