Research Article

Decoupling Suspension Controller Based on Magnetic Flux Feedback

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The suspension module control system model has been established based on MIMO (multiple input and multiple output) state feedback linearization. We have completed decoupling between double suspension points, and the new decoupling method has been applied to CMS04 magnetic suspension vehicle in national mid-low-speed maglev experiment field of Tangshan city in China. Double suspension system model is very accurate for investigating stability property of maglev control system. When magnetic flux signal is taken back to the suspension control system, the suspension module's antijamming capacity for resisting suspension load variety has been proved. Also, the external force interference has been enhanced. As a result, the robustness and stability properties of double-electromagnet suspension control system have been enhanced.

1. Introduction

Maglev vehicle has minor noise, no pollution safety, and comfort many other advantages, so the maglev traffic has a bright prospect in the future. Maglev vehicle concludes several complex subsystems [1] with coupling relations. The vehicle's suspension and guidance depend on magnetic force, and its traction relies on linear motion actuator. According to the production method of magnetic force, maglev system can be divided into two types: EDS and EMS. EMS can make vehicle suspend on the guideway keeping a certain gap, but suspension system in itself is not stable, so it needs active control. Maglev control technology is one of crucial techniques in suspension system. Maglev vehicle is a typical nonlinear system, and suspension module concludes two coupled suspension points which are connected by a rigid joint. The coupling problem is not obvious on straight guideway, but when maglev vehicle arrives at the vertical curve and the curved guideway, the coupling problem can make maglev system unstable. So how to work out this problem is an imperative thing for maglev engineers. Lin et al. have studied the design of a robust discrete-time sliding mode control (DT-SMC) [2] for a high-precision electrohydraulic actuator (EHA) recently. Ngoc [3]

first proved an explicit criterion for positive linear time-varying differential systems with distributed delay. A new approach can keep stabilization of time-varying nonlinear systems with distributed input delay by feedback of plant's state in paper [4]. The stability bound [5] of the singular perturbation parameter can be obtained by solving a set of matrix inequalities. Control redundancies are proposed [6], for example, the controllable redundancy, observable redundancy, stabilization redundancy, and detectable redundancy. The fuzzy sliding mode control approach [7] can be applied to deal with the output tracking of the uncertain system. Nonlinear value control based on FDM (feedback domination method) is simple and has robustness [8] to some kinds of unknown disturbances. The nonlinear feedback principle is developed [9] using the direct-axis and the quadrature-axis stator voltage as manipulated variables. Roy and Asada have investigated nonlinear feedback control of a gravity assisted under actuated manipulator [10] with application to aircraft assembly. A simple methodology [11] to evaluate harmonic distortion in the frequency domain for circuits and systems made up of a nonlinear high-gain path with a nonlinear feedback network is presented. Think that suspension force is a single function about magnetic flux density, and the relation between suspension force and magnetic density's square is

linear [12]. So we take magnetic flux density back to maglev system for promoting the robustness and stability. CMS04 maglev vehicle designed by NUDT (National University of Defense Technology) is showed in Figure 1.

2. Foundation of Flux Feedback Control Suspension Model

EMS middle- and low-speed maglev vehicle applies modular suspension bogies, and one module concludes two suspension points. Double suspension points' suspension task is accomplished by one suspension controller.

Assume the following:

- (1) the leakage flux of magnetic winding is neglected;
- (2) the magnetic resistances of the ferrite core and rail are neglected; namely, magnetic potential falls on air gap $z(t)$ evenly;
- (3) the inclination angle of magnetic rigid body is minuscule, and active point of magnetic force is considered invariable;
- (4) the action line of load forces is superposed with direction of suspension gap measured;
- (5) distribution of mass of the bracket is even, and the masses of two magnets are equal, so the action point of gravity is superposed on the geometry center O .

Based on above assumptions, the force analysis and geometrical relationship of maglev system are showed in Figure 2.

Signs of Figure 2 are illuminated in Table 1.

2.1. Mathematical Model

2.1.1. Kinematics Equations. When electromagnet module is in condition of balance, we can obtain the equation $\sum F_i = 0$ and $\sum M_i = 0$. The kinematics equations of maglev system can be got as follows:

$$\begin{aligned} \frac{1}{2}M \cdot (\ddot{z}_1 + \ddot{z}_2) &= Mg - F_1 - F_2 + f_1 + f_2, \\ \frac{I}{L} \cdot (\ddot{z}_1 - \ddot{z}_2) &= f_1 \cdot \frac{1}{2}l - f_2 \cdot \frac{1}{2}l - \frac{1}{4}F_1 \cdot l + \frac{1}{4}F_2 \cdot l. \end{aligned} \quad (1)$$

Extract acceleration signals from (1):

$$\begin{aligned} \ddot{z}_1 &= \frac{-2L-3l}{2ML} \cdot F_1 + \frac{-2L+3l}{2ML} \cdot F_2 + \frac{L+3l}{ML} \cdot f_1 \\ &\quad + \frac{L-3l}{ML} \cdot f_2 + g, \\ \ddot{z}_2 &= \frac{-2L+3l}{2ML} \cdot F_1 + \frac{-2L-3l}{2ML} \cdot F_2 + \frac{L-3l}{ML} \cdot f_1 \\ &\quad + \frac{L+3l}{ML} \cdot f_2 + g. \end{aligned} \quad (2)$$

FIGURE 1: CMS04 mid-low-speed maglev vehicle.

FIGURE 2: Suspension system's force analysis map.

Set $A = (-2L - 3l)/2ML$, $B = (-2L + 3l)/2ML$, $C = (L + 3l)/ML$, and $D = (L - 3l)/ML$.

Simplify (2):

$$\begin{aligned} \ddot{z}_1 &= A \cdot F_1 + B \cdot F_2 + C \cdot f_1 + D \cdot f_2 + g, \\ \ddot{z}_2 &= B \cdot F_1 + A \cdot F_2 + D \cdot f_1 + C \cdot f_2 + g. \end{aligned} \quad (3)$$

2.1.2. Electromagnetics Equations. We can get geometrical relationship of parameters in Figure 2. The relation between measurement positions z_1, z_2 and real physical positions d_1, d_2 is

$$\begin{aligned} d_1 &= \frac{1}{2}(z_1 + z) = \frac{3}{4}z_1 + \frac{1}{4}z_2, \\ d_2 &= \frac{1}{2}(z_2 + z) = \frac{1}{4}z_1 + \frac{3}{4}z_2. \end{aligned} \quad (4)$$

Magnetic force equations are as follows:

$$\begin{aligned} F_1 &= \frac{B_1^2 S}{\mu_0}, \\ F_2 &= \frac{B_2^2 S}{\mu_0}. \end{aligned} \quad (5)$$

TABLE 1: Symbols in double suspension points system.

Signs	Signification
N	Number of magnetic coils
R	Magnetic resistance
μ_0	Magnetic permeability of atmosphere $4\pi \times 10^{-7}$ H/m
g	Acceleration of gravitation 9.8 m/s^2
θ	Separation angle between electromagnet axis line and horizon
F_1	Electromagnetic force of suspension point P_1
N_1	Disturbing force of suspension point P_1
L	Total length of electromagnet
$i_1(t)$	Current of magnetic coil in suspension P_1
$u_1(t)$	Voltage of magnetic coil in suspension point P_1
$z_1(t)$	Measured position value in suspension point P_1
$d_1(t)$	Average gap value between guideway and suspension point P_1
S	Magnetic pole area
B	Suspension gap flux density
M	Total mass of suspension system
I	Rotation inertia of electromagnet for O point
d	Distance from guideway to O point
F_2	Electromagnetic force of suspension point P_2
N_2	Disturbing force of suspension point P_2
l	Disturbing force of arm relative to O point
$i_2(t)$	Current of magnetic coil in suspension point P_2
$u_2(t)$	Voltage of magnetic coil in suspension point P_2
$z_2(t)$	Measured position value in suspension point P_2
$d_2(t)$	Average gap value between guideway and suspension point P_2

2.1.3. *Electricity Equations.* Voltage balance equations of electromagnet winding are denoted in (6):

$$\begin{aligned} u_1 &= \frac{2Rd_1}{\mu_0 N} B_1 + NS\dot{B}_1, \\ u_2 &= \frac{2Rd_2}{\mu_0 N} B_2 + NS\dot{B}_2. \end{aligned} \quad (6)$$

Substituting (4) into (6), we get

$$\begin{aligned} u_1 &= \frac{R(3z_1 + z_2)}{2\mu_0 N} \cdot B_1 + NS\dot{B}_1, \\ u_2 &= \frac{R(z_1 + 3z_2)}{2\mu_0 N} \cdot B_2 + NS\dot{B}_2. \end{aligned} \quad (7)$$

From (7), we obtain

$$\dot{B}_1 = \varphi_1 = -\frac{R(3z_1 + z_2)}{2\mu_0 SN^2} \cdot B_1 + \frac{1}{NS} \cdot u_1, \quad (8)$$

$$\dot{B}_2 = \varphi_2 = -\frac{R(z_1 + 3z_2)}{2\mu_0 SN^2} \cdot B_2 + \frac{1}{NS} \cdot u_2.$$

On all accounts, the dynamic law of maglev system can be determined by the following equations:

$$\begin{aligned} \ddot{z}_1 &= A \cdot \frac{B_1^2 S}{\mu_0} + B \cdot \frac{B_2^2 S}{\mu_0} + C \cdot f_1 + D \cdot f_2 + g, \\ \ddot{z}_2 &= B \cdot \frac{B_1^2 S}{\mu_0} + A \cdot \frac{B_2^2 S}{\mu_0} + D \cdot f_1 + C \cdot f_2 + g, \end{aligned} \quad (9)$$

$$\dot{B}_1 = \varphi_{11} = -\frac{R(3z_1 + z_2)}{2\mu_0 SN^2} \cdot B_1 + \frac{1}{NS} \cdot u_1,$$

$$\dot{B}_2 = \varphi_{12} = -\frac{R(z_1 + 3z_2)}{2\mu_0 SN^2} \cdot B_2 + \frac{1}{NS} \cdot u_2.$$

2.2. *State-Space Equations.* Choose $x = [x_1, x_2, x_3, x_4, x_5, x_6]^T = [z_1, \dot{z}_1, z_2, \dot{z}_2, B_1, B_2]^T$ as state variable vectors, and the state-space model of maglev system is given as follows:

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= A \cdot \frac{x_5^2 S}{\mu_0} + B \cdot \frac{x_6^2 S}{\mu_0} + C \cdot f_1 + D \cdot f_2 + g, \\ \dot{x}_3 &= x_4, \\ \dot{x}_4 &= B \cdot \frac{x_5^2 S}{\mu_0} + A \cdot \frac{x_6^2 S}{\mu_0} + D \cdot f_1 + C \cdot f_2 + g, \\ \dot{x}_5 &= -\frac{R \cdot (3x_1 + x_3)}{2\mu_0 SN^2} x_5 + \frac{1}{NS} u_1, \\ \dot{x}_6 &= -\frac{R \cdot (x_1 + 3x_3)}{2\mu_0 SN^2} x_6 + \frac{1}{NS} u_2. \end{aligned} \quad (10)$$

Simplify (10):

$$\begin{aligned} \dot{x} &= f(x) + g(x) \cdot u, \\ y &= h(x), \end{aligned} \quad (11)$$

where

$$f(x) = \begin{bmatrix} A \cdot \frac{x_5^2 S}{\mu_0} + B \cdot \frac{x_6^2 S}{\mu_0} + C \cdot f_1 + D \cdot f_2 + g \\ B \cdot \frac{x_5^2 S}{\mu_0} + A \cdot \frac{x_6^2 S}{\mu_0} + D \cdot f_1 + C \cdot f_2 + g \\ -\frac{R \cdot (3x_1 + x_3)}{2\mu_0 S N^2} x_5 \\ -\frac{R \cdot (x_1 + 3x_3)}{2\mu_0 S N^2} x_6 \end{bmatrix}, \quad (12)$$

$$g(x) = [g_1(x) \quad g_2(x)] = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{1}{NS} & 0 \\ 0 & \frac{1}{NS} \end{bmatrix},$$

$$h(x) = \begin{bmatrix} h_1(x) \\ h_2(x) \end{bmatrix} = \begin{bmatrix} x_1 \\ x_3 \end{bmatrix}, \quad u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}.$$

Theorem 1. MIMO affine nonlinear system is described as

$$\begin{aligned} \dot{x} &= f(x) + \sum_{i=1}^m g_i(x) u_i, \\ y &= h(x). \end{aligned} \quad (13)$$

Set the equilibrium point $x_0 \in X$. The problem of MIMO nonlinear system feedback linearization will have a solution, if and only if a neighborhood U near x_0 and m functions $h_1(x), \dots, h_m(x)$ exists. The solution makes relative degree $(r_1, \dots, r_m)$ of nonlinear system (11) satisfy $r_1 + r_2 + \dots + r_m = n$, where n denotes the dimension of system and m stands for input dimension.

2.3. Demonstration of Definition 1. Define the equilibrium point of maglev system $x_0 = [z_{10}, \dot{z}_{10}, z_{20}, \dot{z}_{20}, i_{10}, i_{20}]^T$, and suppose state variables $x_1, x_2, x_5, x_6 \in R_+$, according to real maglev system construction. Compute the vector field as follows, by $f(x)$ and $g(x)$:

$$\begin{aligned} L_{g_1} L_f^0 h_1(x) &= 0, & L_{g_2} L_f^0 h_1(x) &= 0, \\ L_{g_1} L_f h_1(x) &= 0, & L_{g_2} L_f h_1(x) &= 0, \\ L_{g_1} L_f^2 h_1(x) &= \frac{2A \cdot x_5}{\mu_0 N} \neq 0, & L_{g_2} L_f^2 h_1(x) &= \frac{2B \cdot x_6}{\mu_0 N} \neq 0, \\ L_{g_1} L_f^0 h_2(x) &= 0, & L_{g_2} L_f^0 h_2(x) &= 0, \\ L_{g_1} L_f h_2(x) &= 0, & L_{g_2} L_f h_2(x) &= 0, \\ L_{g_1} L_f^2 h_2(x) &= \frac{2B \cdot x_5}{\mu_0 N} \neq 0, & L_{g_2} L_f^2 h_2(x) &= \frac{2A \cdot x_6}{\mu_0 N} \neq 0. \end{aligned} \quad (14)$$

Namely, above equations satisfy

$$L_{g_j} L_f^k h_i(x) = 0, \quad \forall x \in V, \quad 1 \leq j \leq m, \quad 1 \leq i \leq m, \quad 0 \leq k \leq r_i - 2, \quad (15)$$

$$L_{g_j} L_f^{r_i} h_i(x) \neq 0,$$

where

$$\begin{aligned} H(x) &= \begin{bmatrix} L_{g_1} L_f^{r_1-1} h_1(x) & L_{g_2} L_f^{r_1-1} h_1(x) \\ L_{g_1} L_f^{r_2-1} h_2(x) & L_{g_2} L_f^{r_2-1} h_2(x) \end{bmatrix} \\ &= \begin{bmatrix} \frac{2A \cdot x_5}{\mu_0 N} & \frac{2B \cdot x_6}{\mu_0 N} \\ \frac{2B \cdot x_5}{\mu_0 N} & \frac{2A \cdot x_6}{\mu_0 N} \end{bmatrix}. \end{aligned} \quad (16)$$

At the moment, $\det H(x) = 4(A^2 - B^2) \cdot x_5 x_6 / \mu_0^2 N^2 \neq 0$; then $E(x)$ is not singular. Relative degree of maglev system is $(r_1, r_2) = (3, 3)$, and

$$r = \sum_{i=1}^2 r_i = 6 = n. \quad (17)$$

Therefore, Theorem 1 has been proved.

2.4. MIMO Double Suspension Points Model with Feedback Linearization. Compute the vector field generated by $f(x)$ and $h(x)$ as follows:

$$\begin{aligned} L_f^3 h_1(x) &= \frac{1}{\mu_0^2 N^2} [-AR(3x_1 + x_3)x_5^2 - BR(x_1 + 3x_3)x_6^2], \\ L_f^3 h_2(x) &= \frac{1}{\mu_0^2 N^2} [-BR(3x_1 + x_3)x_5^2 - AR(x_1 + 3x_3)x_6^2]. \end{aligned} \quad (18)$$

Design feedback control value $u = H^{-1}(x)[-b(x) + v]$, where the terms $u = [u_1 \quad u_2]^T$, $v = [v_1 \quad v_2]^T$, and

$$H^{-1}(x) = \frac{\mu_0 N}{2(A^2 - B^2)} \cdot \begin{bmatrix} \frac{A}{x_5} & -\frac{B}{x_6} \\ -\frac{B}{x_5} & \frac{A}{x_6} \end{bmatrix},$$

$$b(x) = [L_f^{r_1} h_1(x) \quad L_f^{r_2} h_2(x)]^T = [L_f^3 h_1(x) \quad L_f^3 h_2(x)]^T. \quad (19)$$

We can obtain the control value after linearization from (19):

$$u = H^{-1}(x) [-b(x) + v]$$

$$= \begin{cases} \frac{\mu_0 N}{2(A^2 - B^2)} \cdot \left[-\frac{A}{x_5} \cdot L_f^3 h_1(x) + \frac{B}{x_6} \cdot L_f^3 h_2(x) \right. \\ \quad \left. + \frac{A}{x_5} \cdot v_1 - \frac{B}{x_6} \cdot v_2 \right] \\ \frac{\mu_0 N}{2(A^2 - B^2)} \cdot \left[\frac{B}{x_5} \cdot L_f^3 h_1(x) - \frac{A}{x_6} \cdot L_f^3 h_2(x) \right. \\ \quad \left. - \frac{B}{x_5} \cdot v_1 + \frac{A}{x_6} \cdot v_2 \right] \end{cases} \quad (20)$$

The diffeomorphic mapping matrix is

$$\Phi(x) = \begin{bmatrix} h_1(x) \\ L_f h_1(x) \\ L_f^2 h_1(x) \\ h_2(x) \\ L_f h_2(x) \\ L_f^2 h_2(x) \end{bmatrix} \quad (21)$$

$$= \begin{bmatrix} x_1 \\ x_2 \\ A \cdot \frac{x_5^2 S}{\mu_0} + B \cdot \frac{x_6^2 S}{\mu_0} + C \cdot f_1 + D \cdot f_2 + g \\ x_3 \\ x_4 \\ B \cdot \frac{x_5^2 S}{\mu_0} + A \cdot \frac{x_6^2 S}{\mu_0} + D \cdot f_1 + C \cdot f_2 + g \end{bmatrix}.$$

Choose the coordinates of transformation by matrix $\Phi(x)$:

$$\delta = \begin{bmatrix} h_1(x) & L_f h_1(x) & L_f^2 h_1(x) & h_2(x) & L_f h_2(x) & L_f^2 h_2(x) \end{bmatrix}^T. \quad (22)$$

In sum, maglev control system model after linearization is showed as follows:

$$\begin{aligned} \dot{\delta} &= \Psi \delta + T v, \\ y &= \Omega \delta, \end{aligned} \quad (23)$$

where

$$\Psi = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad T = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}, \quad (24)$$

$$\Omega = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}.$$

Maglev system after feedback linearization is expressed by two-level integral subsystems:

$$G(s) = \begin{bmatrix} \frac{1}{s^3} & 0 \\ 0 & \frac{1}{s^3} \end{bmatrix}. \quad (25)$$

Double suspension points' closed control block diagram with magnetic flux feedback is showed in Figure 3.

3. Design of Suspension Controller

Controlled matrix of system (23) is

$$M_c = [T \quad \Psi T \quad \Psi^2 T \quad \Psi^3 T \quad \Psi^4 T \quad \Psi^5 T]$$

$$= \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}. \quad (26)$$

Because of rank $(M_c) = 6$, maglev system after linearization is controlled completely. So we design double suspension controller for regulating control properties of suspension system:

$$\begin{aligned} v_1 &= K_{p1} \cdot (d_1 - z_0) + K_{d1} \cdot \dot{d}_1 + K_{i1} \cdot \int (d_1 - z_{10}) \cdot dt, \\ v_2 &= K_{p2} \cdot (d_2 - z_0) + K_{d2} \cdot \dot{d}_2 + K_{i2} \cdot \int (d_2 - z_{20}) \cdot dt. \end{aligned} \quad (27)$$

The geometrical relationship between measured positions and real physical positions in (28) is as follows:

$$\begin{aligned} d_1 &= \frac{3}{4} z_1 + \frac{1}{4} z_2, \\ d_2 &= \frac{1}{4} z_1 + \frac{3}{4} z_2. \end{aligned} \quad (28)$$

FIGURE 3: Double suspension points' control construction diagram with feedback linearization.

We can get

$$\begin{aligned}
 v_1 &= K_{p1} \cdot \left(\frac{3}{4}z_1 + \frac{1}{4}z_2 - z_{10} \right) + K_{d1} \cdot \dot{z}_1 \\
 &\quad + K_{i1} \cdot \int \left(\frac{3}{4}z_1 + \frac{1}{4}z_2 - z_{10} \right) \cdot dt, \\
 v_2 &= K_{p2} \cdot \left(\frac{1}{4}z_1 + \frac{3}{4}z_2 - z_{20} \right) + K_{d2} \cdot \dot{z}_2 \\
 &\quad + K_{i2} \cdot \int \left(\frac{1}{4}z_1 + \frac{3}{4}z_2 - z_{20} \right) \cdot dt.
 \end{aligned} \tag{29}$$

By now, double suspension points' controller based on magnetic flux feedback was completed. Construction of the controller is described in Figure 4.

4. Experiments

Some experiments have been completed on CMS04 suspension bogie designed by NUDT (National University of Defense Technology), which is showed in Figure 5. These experiments conclude experiment S1 and experiment S2. Algorithm S1: traditional position-current double cascade

TABLE 2: Standard maglev bogie parameters of CMS04 maglev vehicle.

Parameters	Values
m [kg]	653
N [integer]	324
A [m ²]	0.0235
R [Ω]	0.5
z_0/m	0.008
B_0/T	23
g	9.8
μ_0	$4\pi \times 10^{-7}$

suspension PID control method. Algorithm S2: magnetic flux feedback control algorithm based on MIMO feedback linearization. Initial suspension gap of maglev system is 25 mm, and the set value is 10 mm. Decoupling control experiment has been implemented on CMS04 maglev control experiment platform.

Standard maglev bogie's parameters are given in Table 2.

Decoupling property test comes true on one suspension point of maglev bogie. Set expected position 10 mm.

FIGURE 4: Block diagram of double suspension points system.

FIGURE 5: CMS04 maglev control experiment platform based on magnetic flux feedback.

FIGURE 6: Position curves of algorithm S1.

When maglev system becomes stable, we add additional square signal with amplitude 0.5 mm and period 4 s. Observe suspension signals with two control algorithms S1 and S2. Experiment results are showed in Figures 6 and 7.

Experiment results illustrate that when double suspension control system applies algorithm S2, the dynamic decoupling problem has been worked out. S2 raises the robustness and stability properties of maglev control system, but method S1 has no decoupling effect.

5. Conclusions

Double suspension control model has been founded with magnetic flux signal based on MIMO feedback linearization.

The feedback linearization algorithm enables accurate linearizing model to keep all properties of original nonlinear system which overcome the disadvantages of Taylor's expansion linearization method. In order to work out dynamic coupling problem and external interference problem of EMS mid-low-speed maglev vehicle, we take magnetic flux signal back to maglev control system and design double suspension compensable controller. Some experiments about new algorithm have been done in maglev vehicle CMS04 designed by NUDT. Experiment results demonstrate that double suspension module is precise based on MIMO state feedback linearization theory. With magnetic flux feedback, the maglev control system has better robustness and adaptability than traditional algorithm.

FIGURE 7: Position curves of algorithm S2.

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References

- [1] P. Gáspár, Z. Szabó, G. Szederkényi, and J. Bokor, "Design of a two-level controller for an active suspension system," *Asian Journal of Control*, vol. 14, no. 3, pp. 664–678, 2012.
- [2] Y. Lin, Y. Shi, and R. Burton, "Modeling and robust discrete-time sliding-mode control design for a fluid power electrohydraulic actuator (EHA) system," *IEEE Transactions on Mechatronics*, vol. 18, no. 1, pp. 1–10, 2013.
- [3] P. H. A. Ngoc, "Stability of positive differential systems with delay," *IEEE Transaction on Automatic Control*, vol. 58, no. 1, pp. 203–209, 2013.
- [4] F. Mazenc, S.-I. Niculescu, and M. Bekaik, "Stabilization of time-varying nonlinear systems with distributed input delay by feedback of plant's state," *IEEE Transactions on Automatic Control*, vol. 58, no. 1, pp. 264–269, 2013.
- [5] W.-H. Chen, G. Yuan, and W. X. Zheng, "Robust stability of singularly perturbed impulsive systems under nonlinear perturbation," *IEEE Transactions on Automatic Control*, vol. 58, no. 1, pp. 168–174, 2013.
- [6] Z. Yang, S. Hua, Q. Hongzhuan, and L. Chengrui, "Control reconfigurability of nonlinear system based on control redundancy," in *Proceedings of the 10th IEEE International Conference on Industrial Informatics (INDIN '12)*, pp. 815–820, 2012.
- [7] C.-C. Chiang and C.-H. Wu, "Output tracking control for uncertain underactuated systems based on fuzzy sliding mode control approach," in *Proceedings of the IEEE International Conference on Fuzzy Systems (FUZZ-IEEE '12)*, pp. 1–8, 2012.
- [8] C. Naichao and M. Shengwei, "Nonlinear stabilizing of multi-machine power systems based on feedback domination method," in *Proceedings of the 27th Chinese Control Conference (CCC '08)*, pp. 412–416, July 2008.
- [9] H. Ren and D. Liu, "Nonlinear feedback control of chaos in permanent magnet synchronous motor," *IEEE Transactions on Circuits and Systems II*, vol. 53, no. 1, pp. 45–50, 2006.
- [10] B. Roy and H. H. Asada, "Nonlinear feedback control of a gravity-assisted underactuated manipulator with application to aircraft assembly," *IEEE Transactions on Robotics*, vol. 25, no. 5, pp. 1125–1133, 2009.
- [11] S. O. Cannizzaro, G. Palumbo, and S. Pennisi, "Effects of nonlinear feedback in the frequency domain," *IEEE Transactions on Circuits and Systems I*, vol. 53, no. 2, pp. 225–234, 2006.
- [12] W.-Q. Zhang, *Study and realization on suspension control based on magnetic flux feedback [M.S. thesis]*, National University of Defense Technology, 2009.