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Control Boost of an Active Magnetic Bearing System with DOBs

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KEYWORDS: Active magnetic bearing, Control boost, Disturbance observer

Active magnetic bearing (AMB) spindle with variable-speed derives were verified to have notable improvement in terms of not only energy and cost saving but also size and noise. Digital, internally controlled, magnetic bearings reduce friction and eliminate the need for oil lubrication while a variable speed drive on the motor allows the spindle to operate much more efficiently at partial loads. However, AMB is often subject to disturbances in the form of synchronous vibrations due to unmodeled dynamics such as the rotor mass-imbalance and centrifugal forces. This paper presents control boost of an active magnetic bearing with disturbance observer (DOB). Although the DOB is one of the most popular robust control tools due to its simplicity, flexibility and efficiency, AMB industry still relies heavily relies on the conventional PID control. In this study, the DOBs are applied to current and position control of an active magnetic bearing system and verified to have the control boost in terms of stability and robustness.

NOMENCLATURE

A = State Matrix
$a_{2,1}$, $a_{2,3}$, $a_{3,3}$ = The Element of Matrix A
B = Input Matrix
b_3 = The Element of Matrix B
C = Output Matrix
c_i = Leakage Current of the Electromagnet
d = Disturbance
F_{em} = Electromagnetic Force
F_{emP1} = Coil Inductance
F_{emP2} = Coefficients of Electromagnetic Force
f_i = Time Constant of the Electromagnet
g = Gravity Acceleration
k_i = Voltage-Current Static Gain
kk = Voltage-Force gain of the Electromagnet $(= m \times a_{2,3} \times k_i)$
m = Mass of the Steel Ball
MLS = Magnetic Levitation System
r = Reference Command
s = Laplace Complex Variable
τ = Time Constant of Q Filter
u = Control Effort (Voltage)
x_1, x_2, x_3, x_0 = State Space (The Position of the Iron Ball, Velocity of the Iron Ball, Current, Equilibrium State)
y = Output

1. Introduction

Magnetic levitation technology has advantages such as non-contact, quiet operation, and high efficiency, and is used in various applications such as a magnetic levitation train, and magnetic bearings are also used in molecular pumps and chillers [1,2].

Active magnetic bearing (AMB) spindle with variable-speed derives were verified to have notable improvement in terms of not only energy and cost saving but also size and noise [3]. Digital, internally controlled, magnetic bearings reduce friction and eliminate the need for oil lubrication while a variable speed drive on the motor allows the spindle to operate much more efficiently at partial loads.

The Magnetic Levitation System (MLS) is a nonlinear system that controls the position of an object by regulating the current of the coil through input voltage and generating magnetic force [4]. AMB is often subject to disturbances in the form of synchronous vibrations due to unmodeled dynamics such as the rotor mass-imbalance and centrifugal forces. In addition, there is a change of the inertia or load of AMB system.

Disturbance Observer (DOB) can effectively remove disturbance with a simple structure [5-7]. However, there are not many experimental studies on the disturbance removal and command-following performance improvement using MLS, and most of them are based on the state space model [8, 9].

This paper presents control boost of an active magnetic bearing with disturbance observer (DOB). Although the DOB is one of the most popular robust control tools due to its simplicity, flexibility and efficiency, AMB industry still relies heavily relies on the conventional PID control. In this study, the DOBs are applied to current and displacement control of an active magnetic bearing system and verified to have the control boost in terms of stability and robustness.

2. System Modeling

2.1 Magnetic levitation system

MLS is a non-linear system that measures the position of an object (a metal ball) and levitates it with electromagnetic force by regulating a coil current with voltage. Fig. 1 shows the MLS and the schematic mathematical model used in the experiment. u is the electromagnet coil voltage, x_1 is the ball position, x_3 is the coil current, m is the ball mass and g is the acceleration of gravity.

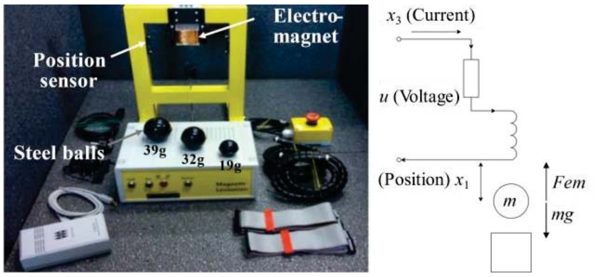


Fig. 1 MLS [10]

2.2 Modeling

Eq. (1-4) shows the nonlinear mathematical model of MLS. F_{em} is the electromagnetic force, F_{emP1} is the coil inductance, F_{emP2} is the electromagnetic force related coefficient, k_i is the static gain of current-voltage, and f_i is the time constant of the electromagnet.

$$\dot{x}_1 = x_2 \tag{1}$$

$$\dot{x}_2 = -\frac{F_{em}}{m} + g \tag{2}$$

$$\dot{x}_3 = \frac{1}{f_i}(k_i u + c_i - x_3) \tag{3}$$

$$F_{em} = x_3^2 \frac{F_{emP1}}{F_{emP2}} exp(-\frac{x_1}{F_{emP2}}) \tag{4}$$

By linearizing Eq. (1-4) at the equilibrium point x_1 = 0.01 m, the system equation can be expressed with Eq. (5). A, B and C are the system, input and output matrices, respectively. The parameters of MLS are shown in Table 1.

$$\dot{x} = Ax + Bu\,, \qquad y = Cx \tag{5}$$

$$Here,\; A = \begin{bmatrix} 0 & 1 & 0 \\ a_{2,1} & 0 & a_{2,3} \\ 0 & 0 & a_{3,3} \end{bmatrix},\; B = \begin{bmatrix} 0 \\ 0 \\ b_3 \end{bmatrix},\; C = [1 \quad 0 \quad 0]$$

$$a_{2,1} = \frac{x_{30}^2}{m}\frac{F_{emP1}}{F_{emP2}} e^{-\frac{x_{10}}{F_{emP2}}},\; a_{2,3} = \frac{2x_{30}}{m}\frac{F_{emP1}}{F_{emP2}} e^{-\frac{x_{10}}{F_{emP2}}},$$

$$a_{3,3} = -f_i^{-1}\,,\; and \quad b_3 = k_i f_i^{-1}.$$

Table.1 Parameters of MLS

Symbol	Description	Value
c_i	Leakage Current	0.0243[A]
f_i	Time Constant	0.0321[s]
F_{emP1}	Coil Inductance	$1.7521\cdot10^{-2}$[H]
F_{emP2}	Coefficients of Electromagnetic Force	$5.8231\cdot10^{-3}$[m]
g	Gravity Acceleration	9.81[m/s^2]
k_i	Voltage-Current Static Gain	2.6903[A/V]
m	Steel Ball Mass	0. 032[kg]
x_{10}	Equilibrium Position of the Steel Ball	0.01[m]
x_{30}	Equilibrium Current	0.6322[A]

3. DOB

3.1 Voltage-controlled MLS

DOB basically estimates and removes disturbances in the dynamic system, as shown in Fig. 2. The control system used consists of a controller (PID), a filter, and a real plant (MLS). Here, r, u, y are reference input, control input, and output, respectively, and d is disturbance. kk is the voltage-force gain of the electromagnet driver, as shown in Eq. (6) [11].

$$kk = m \times a_{2,3} \times k_i \tag{6}$$

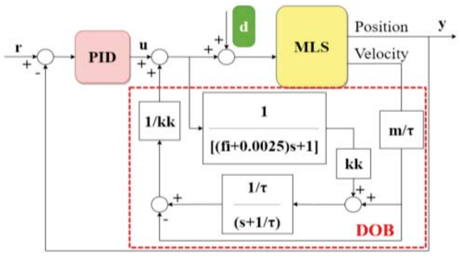


Fig. 2 Schematic of the MLS with PID and DOB

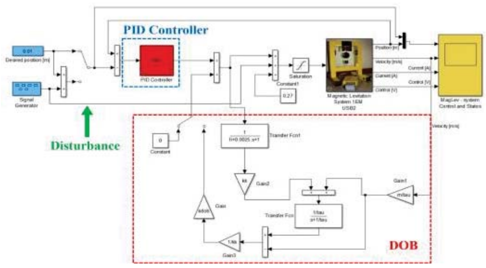


Fig. 3 Simulink realtime block diagram of the MLS with DOB

When the nominal mass of the metal ball is 32 g and the sinusoidal disturbance is 0.01V (about 0.0184N), the disturbance rejection response according to the disturbance frequency change is shown in Fig. 4. Although low-frequency disturbances are well removed by DOB, the disturbance removal performance deteriorates as the disturbance frequency increases. The rejection ratio are 83.6%, 84.5%, 65.3% and 34.5% at 0.5, 1, 1.5 and 2 H, respectively.

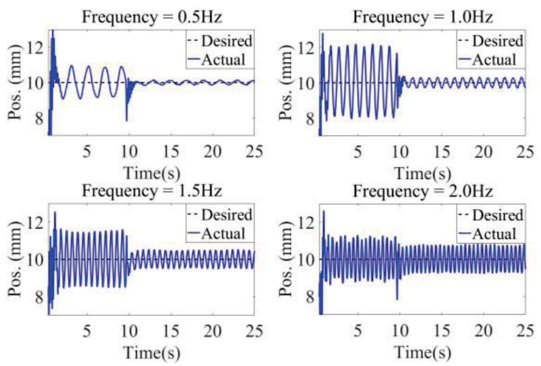


Fig. 4 Disturbance rejection of the MLS with DOB against different disturbance frequencies

Fig. 5 shows the disturbance rejection performance by changing the mass of the steel ball at 1.0Hz disturbance. As the mass increased, the system response slowed and the disturbance rejection performance was improved. The rejection ratio are 79.9%, 85.5% and 90.2% with 19, 32 and 39 g, respectively.

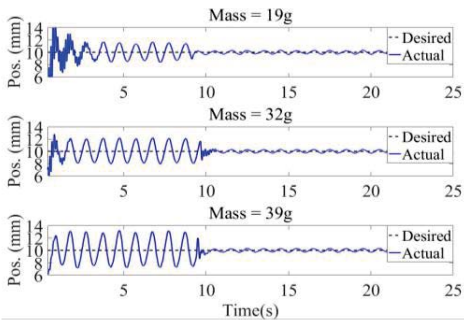


Fig.5 Disturbance rejection of the MLS of different masses W/T DOB

A command-following was evaluated for a sinusoidal input with a frequency amplitude of 0.001 m. Fig. 6 shows the command-following performance according to the frequency increase when the mass of the steel ball is 32g. The command-following performance improved by 60.7% on average with DOB.

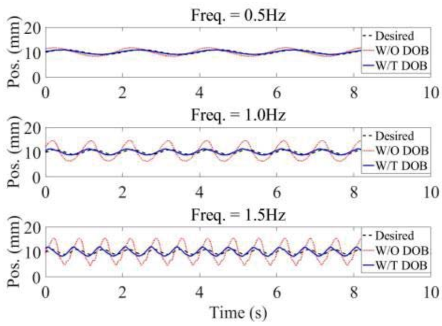


Fig. 6 Command following of the MLS with DOB for different command frequencies (mass=32g)

Command-following at 1Hz was performed according to the change in the mass of the steel ball and shown in Fig. 7. With DOB, command-following performance improved on average by 68.6%.

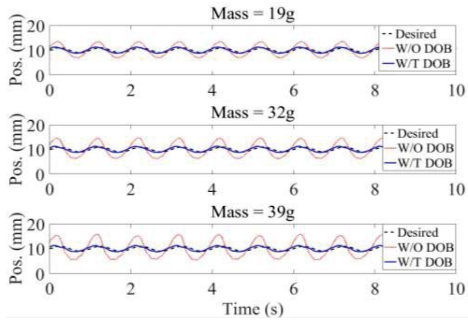


Fig.7 Command following of the MLS of different masses W/T DOB (@1Hz)

3.2 Current-controlled MLS

The current-controlled MLS is shown in Fig. 8 and it consists of PI current control, PID position control, current and position DOB.

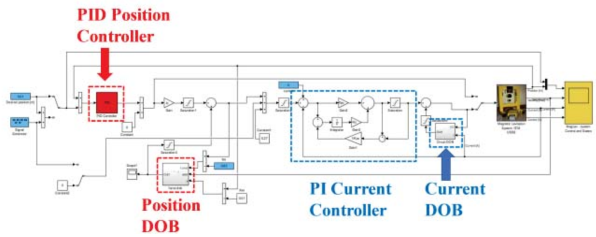
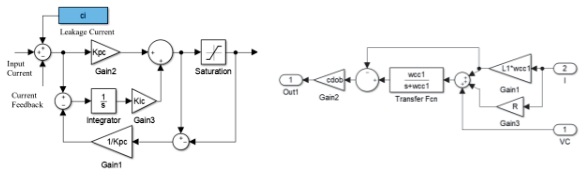


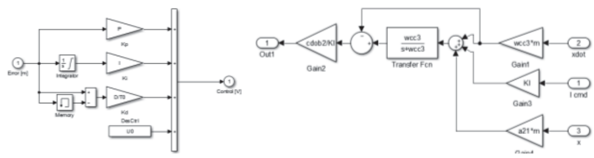
Fig. 8 The current controlled MLS Control System

The PI current controller and its DOB structure are shown in Fig. 9. K_{pc} and K_{ic} are the proportional and integral gains for current control. The PID position controller and its DOB are shown in Fig. 10 K_I is the current-force gain of the electromagnet actuator, wcc3 is the Q filter cut-off frequency, and m is the metal ball mass.



(a) Current PI controller (b) Current control DOB

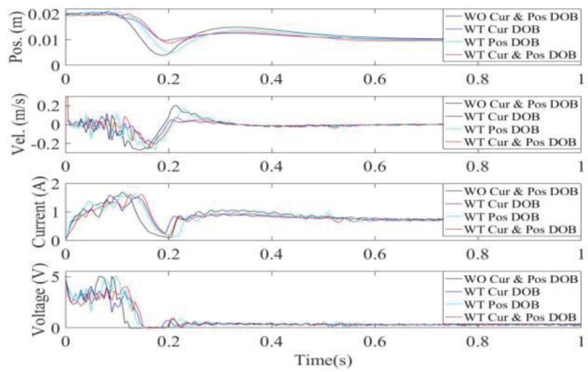
Fig. 9 Structure of the current controller



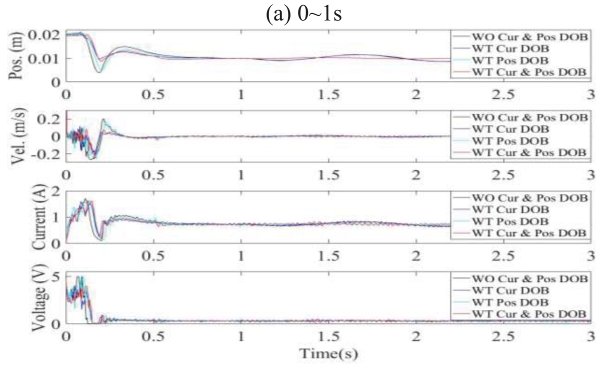
(a) PID controller (b) Position control DOB

Fig. 10 Structure of the PID controller and position control DOB

Using current and position control DOB, a steel ball was levitated and a control performance was evaluated during initial levitation, as shown in Fig. 11. If the current control DOB is used, the settling time is reduced by 0.06s on average, and the maximum overshoot is reduced by about 28%, as shown in Fig. 11(a) Them we turned on the position control DOB after 0.5 sec of levitation and applied a sinusoidal disturbance in 1 sec. Disturbance was effectively eliminated with the position-controlled DOB, as shown in Fig. 11(b).



(a) 0~1s



(b) 0~3s

Fig. 11 The MLS W/T and W/O current and position DOBs

The disturbance rejection was evaluated with disturbances of various frequencies and shown in Fig. 12. The disturbances were effectively removed with position DOB.

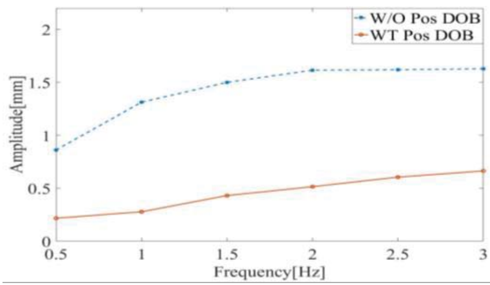


Fig. 12 Disturbance rejection of the MLS with Position DOB

3. Conclusions

This paper presents control boost of an active magnetic bearing with disturbance observer (DOB). The DOBs were applied to current and position control of an active magnetic bearing system and verified to have the control boost in terms of stability and robustness. First, a DOB is designed based on the voltage-controlled MLS. In the experiment, the disturbance rejection and command tracking performances are improved by 76.1% and 64.7% respectively by using DOB. Second, DOBs were applied to current-controlled MLS. The current control DOB compensates inductance change according to the position of the steel ball while position control DOB improved the disturbance removal performance. When DOB is applied to PI current control, the settling time is reduced by 0.06s and the maximum overshoot is reduced by 28% during initial levitation. When DOB is applied to position control, the frequency range 0~3Hz disturbance is removed by 69.1% on average.

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