Robust $\mathcal{H}_\infty$ DIA Control of Levitated Steel Plates

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Keywords: $\mathcal{H}_\infty$ DIA control, magnetic suspension system, robust control, levitated steel plate

This paper deals with an application of $\mathcal{H}_\infty$ DIA control to the magnetically levitated steel plates. The magnetically levitated steel plate technology is expected to prevent a surface quality of steel plate from deteriorating in a manufacturing process. The multiple steel plates levitation problem by a single controller has not been studied and the robust control system design for multiple plates are expected.

Our goal in this research is to suspend two thin steel plates stably by using four electromagnets without any physical contacts. We apply the robust $\mathcal{H}_\infty$ DIA control approach to the magnetically levitated steel plates. The $\mathcal{H}_\infty$ DIA control problem treats a mixed Disturbance and an Initial state uncertainty Attenuation and it is expected to provide a good transient property to a control system.

We have constructed an experimental system for levitated steel plates shown in Fig. 1. This system has five electromagnets and four of them are used in the feedback control in this research. Detail specification of two steel plates used in experiments is described in Table 1.

Fig. 1. Magnetically Levitated Steel Plates

A mathematical model of the system was derived where we assumed that the whole system can be divided to four independent subsystems. Four SISO control systems are designed individually by the $\mathcal{H}_\infty$ DIA control.

Then we set the generalized plant which contains design parameters for uncertainties and control performance, and designed an $\mathcal{H}_\infty$ DIA controller.

We conducted control experiments for two plates in Table 1 and evaluated control and robustness properties of the designed $\mathcal{H}_\infty$ DIA controller compared with the conventional PID controller. The

Table 1. Two Steel Plates

	Plate 1	Plate 2
Width	500 [mm]	500 [mm]
Depth	500 [mm]	500 [mm]
Thickness	0.3 [mm]	0.5 [mm]
Mass	0.537 [kg]	0.937 [kg]

Fig. 2. $\mathcal{H}_\infty$ DIA: 0.3 [mm]

Fig. 3. PID: 0.3 [mm]

Fig. 4. $\mathcal{H}_\infty$ DIA: 0.5 [mm]

Fig. 5. PID: 0.5 [mm]

experimental results are shown in Figs. 2–5. They show that our proposed $\mathcal{H}_\infty$ DIA controller suppresses vibration of the steel plates and it has a robust stability for multiple steel plates.

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This paper deals with an application of $\mathcal{H}_\infty$ DIA control to the magnetically levitated steel plates. Our goal in this research is to suspend two thin steel plates stably by using four electromagnets without any physical contacts. We apply the robust $\mathcal{H}_\infty$ DIA control approach to the magnetically levitated steel plates. The $\mathcal{H}_\infty$ DIA control problem treats a mixed Disturbance and an Initial state uncertainty Attenuation and it is expected to provide a good transient property to a control system. Experimental results show that the proposed robust control approach is effective for suppressing an elasticity vibration of steel plates.

Keywords: $\mathcal{H}_\infty$ DIA control, magnetic suspension system, robust control, levitated steel plate

1. Introduction

The magnetically levitated steel plate technology is expected to prevent a surface quality of steel plate from deteriorating in a manufacturing process⁽¹⁾⁽²⁾. This technology can also be applied to magnetic levitated transportation systems⁽³⁾.

In order to make this technology fit for practical use, a feedback controller should be able to suspend multiple steel plates, and to suppress an elasticity vibration of steel plates⁽⁴⁾⁽⁵⁾.

There have been a lot of related works concerning magnetically levitated steel plate technology, e.g., steel plate transport systems, et al. The multiple steel plates levitation problem by a single controller, however, has not been studied and the robust control system design for multiple plates are expected.

Our goal in this research is to suspend two thin steel plates stably by using four electromagnets without any physical contacts. We apply the robust $\mathcal{H}_\infty$ DIA control approach⁽⁸⁾ to the magnetically levitated steel plates.

The $\mathcal{H}_\infty$ DIA control problem treats a mixed Disturbance and an Initial state uncertainty Attenuation and it is expected to provide a good transient property to the control system.

We have constructed an experimental system with four electromagnets for levitated steel plates. We drive a mathematical model of the system where we have assumed that the whole system can be divided to four independent sub-systems.

Four SISO control systems are designed individually by the $\mathcal{H}_\infty$ DIA control theory. Then we set the generalized plant which contains design parameters for uncertainties and control performance, and design $\mathcal{H}_\infty$ DIA controllers for the

generalized plant.

Finally we conduct control experiments for two plates and evaluate control and robustness properties of the designed $\mathcal{H}_\infty$ DIA controller compared with the conventional PID controller. The experimental results show that our proposed $\mathcal{H}_\infty$ DIA controller suppresses a vibration of the steel plates and it has a robust stability for multiple steel plates.

2. Robust $\mathcal{H}_\infty$ DIA Control

Consider the linear time-invariant system.

$$\begin{aligned} \dot{x} &= Ax + B_1w + B_2u, & x(0) &= x_0 \\ z &= C_1x + D_{12}u \\ y &= C_2x + D_{21}w \dots\dots\dots \end{aligned} \quad (1)$$

where $x \in R^n$ is the state and x_0 is the initial state; $u \in R^r$ is the control input; $y \in R^m$ is the observed output; $z \in R^q$ is the controlled output; $w \in R^p$ is the disturbance.

For system (1), a control $u(t)$ is given by linear time-invariant system of the form

$$\begin{aligned} u &= J\zeta + Ky \\ \dot{\zeta} &= G\zeta + Hy, & \zeta(0) &= 0 \dots\dots\dots \end{aligned} \quad (2)$$

which makes the closed-loop system internally stable.

For the system and the controls described above, consider a mixed-attenuation problem as follows.

$\mathcal{H}_\infty$ DIA Control problem⁽⁸⁾

Find a control $u(t)$ attenuating disturbances and initial state uncertainties in the way that, for given $N > 0$, z satisfies

$$\|z\|_2^2 < \|w\|_2^2 + x_0^T N^{-1} x_0 \dots\dots\dots \quad (3)$$

for all $w \in L^2[0, \infty)$ and all $x_0 \in R^n$, s.t., $(w, x_0) \neq 0$.

Such an admissible control is called the **D**isturbance and **I**nitial state uncertainty **A**ttenuation (DIA) control.

In order to solve the problem, we require the following three conditions.

(A1) There exists a solution $M > 0$ to the Riccati equation

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$$\begin{aligned}
& M(A - B_2(D_{12}^T D_{12})^{-1} D_{12}^T C_1) \\
& + (A - B_2(D_{12}^T D_{12})^{-1} D_{12}^T C_1)^T M \\
& - M(B_2(D_{12}^T D_{12})^{-1} B_2^T - B_1 B_1^T) M \\
& + C_1^T C_1 - C_1^T D_{12} (D_{12}^T D_{12})^{-1} D_{12}^T C_1 = 0 \dots\dots\dots (4)
\end{aligned}$$

s.t. $A - B_2(D_{12}^T D_{12})^{-1} D_{12}^T C_1 - B_2(D_{12}^T D_{12})^{-1} B_2^T M + B_1 B_1^T M$ is stable.

(A2) There exists a solution $P > 0$ to the Riccati equation

$$\begin{aligned}
& (A - B_1 D_{21}^T (D_{21} D_{21}^T)^{-1} C_2) P \\
& + P(A - B_1 D_{21}^T (D_{21} D_{21}^T)^{-1} C_2)^T \\
& - P(C_2^T (D_{21} D_{21}^T)^{-1} C_2 - C_1^T C_1) P \\
& + B_1 B_1^T - B_1 D_{21}^T (D_{21} D_{21}^T)^{-1} D_{21} B_1^T = 0 \dots\dots\dots (5)
\end{aligned}$$

s.t. $A - B_1 D_{21}^T (D_{21} D_{21}^T)^{-1} C_2 - P C_2^T (D_{21} D_{21}^T)^{-1} C_2 + P C_1^T C_1$ is stable.

(A3) $\rho(PM) < 1$

where $\rho(X)$ denotes the spectral radius of matrix X . Then we obtained the following results.

Theorem 1⁽⁸⁾

Suppose that the conditions (A1), (A2), (A3) are satisfied. Then the $\mathcal{H}_\infty$ central control is given as

$$\begin{aligned}
u &= -(D_{12}^T D_{12})^{-1} (B_2^T M + D_{12}^T C_1) (I - PM)^{-1} \zeta \\
\dot{\zeta} &= A\zeta + B_2 u + P C_1^T (C_1 \zeta + D_{12} u) \\
&+ (P C_2^T + B_1 D_{21}^T) (D_{21} D_{21}^T)^{-1} (y - C_2 \zeta) \\
\zeta(0) &= 0 \dots\dots\dots (6)
\end{aligned}$$

The $\mathcal{H}_\infty$ central control (6) is a DIA control if and only if the condition (A4) is satisfied.

(A4) $Q + N^{-1} - P^{-1} > 0$,

where Q is the maximal solution of the Riccati equation

$$\begin{aligned}
& Q(A - B_1 D_{21}^T (D_{21} D_{21}^T)^{-1} C_2 \\
& + (B_1 B_1^T - B_1 D_{21}^T (D_{21} D_{21}^T)^{-1} D_{21} B_1^T) P^{-1}) \\
& + (A - B_1 D_{21}^T (D_{21} D_{21}^T)^{-1} C_2 \\
& + (B_1 B_1^T - B_1 D_{21}^T (D_{21} D_{21}^T)^{-1} D_{21} B_1^T) P^{-1})^T Q \\
& - Q(B_1^T - D_{21}^T (D_{21} D_{21}^T)^{-1} (C_2 P + D_{21} B_1^T) L)^T \\
& \times (B_1^T - D_{21}^T (D_{21} D_{21}^T)^{-1} (C_2 P + D_{21} B_1^T) L) Q \\
& = 0 \dots\dots\dots (7)
\end{aligned}$$

with $L := (I - PM)^{-1}$.

3. System Description and Modeling

3.1 Construction We have constructed an experimental system for levitated steel plates shown in Fig. 1, and its model is shown schematically in Fig. 2.

This system has five electromagnets and four of them are used in the feedback control. Each electromagnet has its own optical gap sensor across the steel plate as shown in Fig. 3.

Detail specifications of two steel plates: a 0.3 [mm] thick *Steel Plate 1 (SP1)* and a 0.5 [mm] thick *Steel Plate 2 (SP2)*

Fig. 1. Experimental setup

Fig. 2. System structure

Fig. 3. Position relation between an electromagnet and a sensor

Fig. 4. Magnetically Levitated Steel Plates

used in experiments are described in Table 1. Here the *SP1* is a nominal suspended object and the *SP2* is a perturbed suspended object.

3.2 Mathematical Model In order to derive a model of the system by physical law, we introduce following assumptions.

- The whole system can be divided to four independent Single Input Single Output subsystems.

Table 1. Specifications for the steel plates

	Steel Plate 1	Steel Plate 2
Wide	500 [mm]	500 [mm]
Depth	500 [mm]	500 [mm]
Thickness	0.3 [mm]	0.5 [mm]
Mass	0.537 [kg]	0.937 [kg]

Table 2. System Parameter

Parameter	Symbol	SP1 ^a	SP2 ^b
Mass of a quarter of Steel Plate	m [g]	134	238
Steady Gap	X [m]	5.0×10^{-3}	5.0×10^{-3}
Coefficients of $f(t)$	k [Nm ² /A ²]	8.50×10^{-4}	9.5×10^{-4}
position offset term	x_0 [m]	2.80×10^{-2}	1.15×10^{-3}
Steady Current	I [A]	0.309	0.3595

^a SP1 is Steel Plate 1.^b SP2 is Steel Plate 2

- Four electromagnets are identical (see Fig. 4).

Under these assumptions, we derive the equation of motion of the iron steel plate and the electromagnetic force equation as follows⁽⁹⁾.

$$m \frac{d^2 x(t)}{dt^2} = mg - f(t) + v_m(t) \quad (8)$$

$$f(t) = k \left(\frac{I + i(t)}{X + x(t) + x_0} \right)^2 \quad (9)$$

where m as the mass of the 1/4 steel plate, X as a steady gap between the electromagnet and the steel plate, $x(t)$ as a deviation from X , I as a steady current, $i(t)$ as a deviation from I , $f(t)$ as an electromagnet force, k , x_0 are coefficients of $f(t)$, $v_m(t)$ as a disturbance force.

The electromagnetic force (9) is linearized around the operating point by the Taylor series expansion as

$$f(t) = k \left(\frac{I}{X + x_0} \right)^2 - K_x x(t) + K_i i(t) \quad (10)$$

$$K_x = \frac{2kI^2}{(X + x_0)^3}, \quad K_i = \frac{2kI}{(X + x_0)^2}$$

The sensor provides the information for the gap $x(t)$. Hence the measurement equation can be written as

$$y_g(t) = x(t) + w_0(t) \quad (11)$$

where $w_0(t)$ represents the sensor noise as well as the model uncertainties.

Thus, summing up the above results, the state equations for the system⁽⁹⁾ are

$$\dot{x}_g = A_g x_g + B_g u_g + D_g v_0 \quad (12)$$

$$y_g = C_g x_g + w_0$$

$$x_g := [x \ \dot{x}]^T, u_g := i, v_0 := v_m$$

$$A_g = \begin{bmatrix} 0 & 1 \\ K_x & 0 \end{bmatrix}, B_g = \begin{bmatrix} 0 \\ -K_i \end{bmatrix}, D_g = \begin{bmatrix} 0 \\ 1/m \end{bmatrix}$$

$$C_g = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

4. Control System Design

Let v_0 and w_0 be of the form with the frequency weighting functions W_v and W_w as

$$v_0 = W_v(s) w_2 \quad (13)$$

Fig. 5. Generalized Plant

$$W_v = \Phi C_v (sI - A_v)^{-1} B_v, \quad \Phi = \begin{bmatrix} 1 & 1 \end{bmatrix}^T$$

$$w_0 = W_w w_1, \dots \quad (14)$$

The gap $x(t)$ and the corresponding velocity $\dot{x}(t)$ are restricted by the weight Θ , and the control input $u(t)$ also should be regulated to suppress the energy, where its weight is expressed by ρ ; i.e.,

$$z_1 = \Theta x_g, \quad \Theta = \text{diag} \begin{bmatrix} \theta_1 & \theta_2 \end{bmatrix} \quad (15)$$

$$z_2 = \rho u_g \quad (16)$$

Finally, we can construct the generalized plant (17) in the following;

$$\begin{aligned} \dot{x} &= Ax + B_1 w + B_2 u \\ z &= C_1 x + D_{12} u \\ y &= C_2 x + D_{21} w \end{aligned} \quad (17)$$

$$A = \begin{bmatrix} A_g & D_g C_w \\ 0 & A_w \end{bmatrix}, B_1 = \begin{bmatrix} 0 & D_g D_w \\ 0 & B_w \end{bmatrix}$$

$$B_2 = \begin{bmatrix} B_g \\ 0 \end{bmatrix}, C_1 = \begin{bmatrix} \Theta & 0 \\ 0 & 0 \end{bmatrix}, D_{12} = \begin{bmatrix} 0 \\ \rho \end{bmatrix}$$

$$C_2 = \begin{bmatrix} C_g & 0 \end{bmatrix}, D_{21} = \begin{bmatrix} W_w & 0 \end{bmatrix}$$

where $x := [x_g^T \ x_v^T]^T$ and x_v is a state of $W_v(s)$, $w := [w_1^T \ w_2^T]^T$ and $z := [z_1^T \ z_2^T]^T$.

Now our control problem setup is as followed.

Control Problem Setup: Finding an admissible controller $K(s)$ that attenuates disturbance and initial state uncertainties to achieve DIA condition in (3).

4.1 $\mathcal{H}_\infty$ DIA Controller After some control system design iterations, the final parameter of the $\mathcal{H}_\infty$ DIA Controller was chosen as follows.

$$\begin{aligned} W_v &= \frac{5 \times 10^3}{s + 1.0 \times 10^{-2}} \\ W_w &= 5 \times 10^{-1} \\ \Theta &= \text{diag} \begin{bmatrix} 1 \times 10^{-2} & 1 \times 10^{-4} \end{bmatrix} \\ \rho &= 1 \times 10^{-6} \end{aligned} \quad (18)$$

These design parameters give the $\mathcal{H}_\infty$ DIA controller as follows, where the maximum value of the weighting matrix N is $N = 1.013 \times 10^{-2}$.

$$K_{DIA}(s) = \frac{1.96 \times 10^6 (s + 7.48)(s + 49.3)}{(s + 6250)(s + 224)(s + 9.78 \times 10^{-3})} \quad (19)$$

The frequency response of the $\mathcal{H}_\infty$ DIA controller K_{DIA} is shown in Fig. 6 by a solid line.

Fig. 6. Frequency Responses of Two Controllers

4.2 PID Controller We designed a saturated PID controller for the comparison with the proposed $\mathcal{H}_\infty$ DIA controller. In order to suppress a vibration of the closed-loop system at the high frequency, a gain of the PID controller is saturated at around 100 [Hz]. The transfer function of the final saturated PID controller $K_{PID}(s)$ is as follows.

$$K_{PID}(s) = \frac{K_D s^2 + K_P s + K_I}{s(1 + \frac{K_D/K_P}{N} s)} \dots\dots\dots (20)$$

where

$$K_P = 200, K_I = 150, K_D = 1.0, N = 3$$

The frequency response of the controller $K_{PID}(s)$ is also shown in Fig. 6 by a dashed line.

5. Experimental Evaluation

We conducted experiments to evaluate properties of the $\mathcal{H}_\infty$ DIA controller for steel plate levitation system.

All experimental results shown below are time responses at the electromagnet 1 at P1 in Fig. 4. The other responses at P2-P4 show similar to them at P1.

5.1 Nominal Stability and Performance First we conducted experiments by using the nominal steel plate *SP1*. Steady state position responses for stability evaluation of $\mathcal{H}_\infty$ DIA controller and PID controller are shown in Figs. 7 and 13, respectively. These figures show that $\mathcal{H}_\infty$ DIA control suppress a vibration of the steel plate compared with PID.

Transient step responses for performance evaluation of both controllers are shown in Figs. 8 and 14, respectively. $\mathcal{H}_\infty$ DIA shows relatively bigger overshoot but convergence of the controller is better and the steady state vibration is suppressed.

Figs. 9 and 15 are time responses for step disturbance whose magnitude is about 20 [%] of the steady-state electromagnetic force. $\mathcal{H}_\infty$ DIA shows also relatively bigger overshoot but the steady state vibration is suppressed.

5.2 Robustness for multiple plates Robust stability was checked by using the steel plate *SP2*. Steady state response of $\mathcal{H}_\infty$ DIA control and PID are shown in Figs. 10 and 16, respectively. Both controllers achieve robust stability and the closed-loop system with both controllers are stable for *SP2*.

Table 3. Vibration of center of Steel Plate in Steady State

		<i>SP1</i>	<i>SP2</i>	Increasing Rate
$\mathcal{H}_\infty$ DIA	Maximum Amplitude [mm]	0.2	0.4	+100 [%]
	RMS of vibration [mm]	0.083	0.180	+118 [%]
PID	Maximum Amplitude [mm]	0.3	0.8	+167 [%]
	RMS of vibration [mm]	0.117	0.312	+167 [%]

Our proposed $\mathcal{H}_\infty$ DIA controller suppresses a vibration of the steel plates and it has a robust stability for multiple steel plates. $\mathcal{H}_\infty$ DIA control restrains a deterioration and a vibration compared with PID controller.

Transient step responses of both controllers are shown in Figs. 11 and 17, respectively. Disturbance responses of both controllers are also shown in Figs. 9 and 15.

These are similar to results in the nominal case and the $\mathcal{H}_\infty$ DIA controller suppresses the steady state vibration.

The maximum amplitude of the vibration of time responses and their root mean square value at the steady state in 5 [s] are summarized in Table 3.

Table 3 shows that the $\mathcal{H}_\infty$ DIA controller suppresses the steady state vibration and a deterioration caused by the model perturbation is reduced by the robust $\mathcal{H}_\infty$ DIA controller.

6. Conclusion

This paper dealt with an application of the robust $\mathcal{H}_\infty$ DIA control to the magnetically levitated steel plates.

Our goal in this research was to suspend two thin steel plates *SP1* and *SP2* stably by using four electromagnets. We applied the robust $\mathcal{H}_\infty$ DIA control approach⁽⁸⁾ to the magnetically levitated steel plates.

We have constructed an experimental system with four electromagnets for levitated steel plates. We derived a mathematical model of the system where we assumed that the whole system could be divided to four independent subsystems. Four SISO control systems were designed individually by the $\mathcal{H}_\infty$ DIA control theory. Then we set the generalized plant which contains design parameters for uncertainties and control performance, and designed $\mathcal{H}_\infty$ DIA controllers for the generalized plant.

Finally we conducted several control experiments for two plates and evaluated control and robustness properties of the designed $\mathcal{H}_\infty$ DIA controller compared with the conventional PID controller. The experimental results show that our proposed $\mathcal{H}_\infty$ DIA controller suppressed a vibration of the steel plates in the steady state and it had a robust stability for multiple steel plates.

Next goal is a stable suspension of 1 [mm] thick steel plate without any physical contact by using $\mathcal{H}_\infty$ DIA control and Multi-Input and Multi-Output system representation of the controlled system.

Fig. 7. Steady state of $SP1$ for $\mathcal{H}_\infty$ DIA Fig. 8. Step response of $SP1$ for $\mathcal{H}_\infty$ DIA Fig. 9. Disturbance response of $SP1$ for $\mathcal{H}_\infty$ DIA Fig. 10. Steady state of $SP2$ for $\mathcal{H}_\infty$ DIA Fig. 11. Step response of $SP2$ for $\mathcal{H}_\infty$ DIA Fig. 12. Disturbance response of $SP2$ for $\mathcal{H}_\infty$ DIA Fig. 13. Steady state of $SP1$ for PID Fig. 14. Step response of $SP1$ for PID Fig. 15. Disturbance response of $SP1$ for PID Fig. 16. Steady state of $SP2$ for PID Fig. 17. Step response of $SP2$ for PID Fig. 18. Disturbance response of $SP2$ for PID

References

- (1) T. Nakagawa and M. Hama: "Study of Magnetic Levitation Control by Means of Correcting Gap Length Command for a Thin Steel Plate", *T. IEE Japan*, Vol.120-D, No.4, pp.489–494 (2000) (in Japanese)
- (2) M. Morishita and M. Akashi: "Inclination Guide Experiment for Magnetically Levitated Steel Plates", *1988 National Convention Record, IEEJ*, pp.5–183 (1998) (in Japanese)
- (3) H. Guro and R.W. Baldi: "General Atomics Urban Maglev Test Track Status", *Proc. of The Fifth International Symp. on Linear Drives for Industry Applications*, pp.251–253 (2005)
- (4) Y. Oshino, K. Ishibashi, and T. Sekihara: "Conveyance Control for an Electromagnetic Levitation Rectangular Sheet Steel (Proposition of Non-contact Control Mechanism for the Horizontal Inertial Force of the Steel Plate which Suppressed the Elastic Vibration)", *Trans. on JSME. Series C*, Vol.68, No.669, pp.86–92 (2002) (in Japanese)
- (5) T. Ishiwatari, M. Watada, S. Torii, and D. Ebihara: "Effect of suppressing vibration on thin steel sheet suspended by magnetic levitation control which includes two desired values", *Technical Meeting on Linear Drives, IEEJ, LD-98-37*, pp.43–48 (1998) (in Japanese)
- (6) K. Tada and S. Torii: "The Design Manual of Voltage-Controlled and Current-Controlled Observer in Sensorless Magnetic Levitation System of Steel Plate", *Proc. of The Fifth International Symp. on Linear Drives for Industry Applications*, pp.433–436 (2005)
- (7) M. Castelli, M. Martinez-Iturralde, G. Martinez, A. Garcia Rico, and J. Florez: "Linear Induction Motor Control for Simultaneous Propulsion and Levitation of an Aluminium Plate", *Proc. of The Fifth International Symp. on Linear Drives for Industry Applications*, pp.465–468 (2005)
- (8) T. Namerikawa, M. Fujita, R.S. Smith, and K. Uchida: "On the $\mathcal{H}_\infty$ Control System Design Attenuating Initial State Uncertainties", *Trans. on SICE*, Vol.40, No.3, pp.307–314 (2004)
- (9) M. Fujita, T. Namerikawa, F. Matsumuta, and K. Uchida: " μ -Synthesis of an Electromagnetic Suspension System", *IEEE Trans. on Automatic Control*, Vol.40, No.3, pp.530–536 (1995)

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