# A Time Delay-Based gain Scheduled Control For Electromagnetic Suspension System

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ABSTRACT: This paper proposes a robust gain scheduled control technique using time-delay for the nonlinear systems with model uncertainty and unexpected disturbances. The time-delay-based gain scheduling method depends on a direct estimation of a function representing the effect of uncertainty. The information from the estimation is used to cancel the unexpected disturbances simultaneously. The time-delay-based gain scheduled control uses the past observation of the system's response and the control input to directly modify the control actions rather than to adjust the controller gains or to identify system parameters. The benefits of this proposed scheme are demonstrated in the simulation of an electromagnetic suspension system with model uncertainty and external disturbances, and the method is compared with the conventional state feedback controller.

## 1 INTRODUCTION

The gain scheduled control technology has been proved to be successful in many engineering applications where the fixed gain control does not produce a satisfactory result (J. HUANG *et al.* 1990, J. HUANG *et al.* 1992, W. J. RUGH 1995, I. KAMINER *et al.* 1992). The method, however, has a limitation that the resulting control system works only for systems with constant parameters or sufficiently slow time-varying parameters, which can be well modeled by some scheduling parameters. Recently, in order to improve the regulation performance for a system with relatively fast time-varying parameters, there is proposed a method that utilizes derivative information (N. SURESHBABU *et al.* 1995, S.-H. LEE *et al.* 1997). Also, there are known a class of control design methods (Y. H. CHEN 1993, M. P. GLAZOS *et al.* 1995, S.-H. LEE *et al.* 1997) in which uncertainty is decomposed into two categories; matched uncertainty and mismatched uncertainty. Further a concept of *k*th-order approximate equilibrium point is introduced in (J. HUANG *et al.* 1992, J. HUANG 1995), and then its *k*th-order robust control law is constructed for a class of uncertain nonlinear systems with time-varying parameters. More recently, the $H_\infty$ control has become an effective design methodology for the tracking control problem for uncertain plants in view of stability and robustness. In addition, the fusion of the $H_\infty$ control theory and gain scheduling has been paid a great deal of attention (R. A. NICHOLS *et al.* 1996, P. APKARIAN *et al.* 1995, W. W. LU *et al.* 1995). Especially, it is noted that $H_\infty$ synthesis technique is extended in (P. APKARIAN *et al.* 1995) to allow the controller to be dependent on time-varying but measurable parameters in linear time-varying systems. Using the $H_\infty$ gain scheduled controller, some robust properties were guaranteed at local operating points.

In many practical situations, however, some parameters of the system are either poorly defined or the system operates in the environments where the parameters change in a non-predictable manner. In such situations, the conventional fixed gain control will be inadequate to achieve a satisfactory performance in the entire range. Several advanced control techniques have been developed for such systems, one of which is the time-delay control (I.H. SUH *et al.* 1979, K. YOUCEF-TOUMI. *et al.* 1990, P. H. CHANG *et al.* 1995, T. C. HSIA *et al.* 1990). In this paper, we propose a robust gain scheduled system consisting of the time-delay control and the gain scheduler for the nonlinear systems with external disturbances and parameter uncertainty. In the proposed time-delay gain scheduling method, the effect of uncertainty is directly estimated and the information from estimation is used to cancel the effect of unknown dynamics and unexpected disturbances simultaneously. Also, the proposed estimation scheme with a finite convergence time is formulated in order to estimate the unknown scheduling variable.

As a possible application, we investigate an electromagnetic suspension system model, which represents the essential dynamics of magnetically levitated transport system. The system is highly nonlinear with unstable dynamics. The practical electromagnetic suspension systems have been developed to cope with rail joints and rail irregularities. In fact, absence of contacts of the electromagnetic suspension system reduces noise, component wear, vibration, and need for maintenance, etc. The rail joints and rail irregularities in the track, however, often cause instability of the system and increase the regulation air-gap error at the levitated state. It is very important to decrease the regulation air-gap error for increasing the safety and ride quality of the railway systems realized by magnetically levitated transport system. Typically, the model uncertainty and external disturbances deteriorate the quality of system performance. Recently, there have been reported various nonlinear control schemes in the literatures such as the gain scheduling (C. Y. KIM *et al.* 1994) and the feedback linearization methodology (Y.-S. LU *et al.* 1995, S. J. JOO *et al.* 1997, D. L. TRUMPER *et al.* 1997). In case of the feedback linearization methods (Y.-S. LU *et al.* 1995, S. J. JOO *et al.* 1997, D. L. TRUMPER *et al.* 1997), the nonlinear nature in the electromagnetic suspension system is effectively canceled, but some limitation exists in handling the unknown mass variation and external disturbances. Thus, we propose the time-delay-based gain scheduled control as an extended version of the gain scheduling method, and apply it to the electromagnetic suspension system so as to guarantee the robust performance against the irregular air-gap disturbance and the lift force variation.

The paper is organized as follows. In Section **2**, we design a time-delay-based gain scheduled controller. In Section **3,** we discuss some possible application to a class of magnetically levitated transport system. Then we compare the simulation results of the proposed controller with those of the conventional state feedback controller. Finally, in Section **4,** the results are summarized and concluding remarks are given.

## 2 TIME-DELAY-BASED GAIN SCHEDULED CONTROLLER

Consider the following nonlinear SISO system in phase variable form described as

$$\dot{x}_n(t) = f(\boldsymbol{x}(t), u(t), w(t)) + \Delta f(t), \quad y(t) = h(\boldsymbol{x}(t)), \tag{1}$$

where $\boldsymbol{x}(t) = [x_1(t)\, x_2(t) \cdots x_n(t)\ ]^T \in R^n$ denotes the vector of state variables, $u(t) \in R$ and $y(t) \in R$ are the input and output of the plant, and $w(t) \in R$ denotes a scheduling variable. The functions $f$ and $h$ are assumed to be smooth and $\Delta f(t)$ represents unmodeled dynamics of the system or uncertainty caused by parameter variations. The essential part of the system equation in (1) is rewritten as

$$\dot{x}_n(t) = f(\boldsymbol{x}(t), u(t), w(t)) + \Delta f(t) \cdot \tag{2}$$

In (2), if the uncertainty term $\Delta f(t) = 0$, then we can derive a gain scheduling control law in the regulation problem described by

$$\bar{u}(t) = k(\boldsymbol{x}(t), w(t)), \tag{3}$$

where $k$ is a smooth function such that the closed-loop system has the following properties: at each constant value of the scheduling variable, $w(t) = w_0$, the closed-loop system should have a constant operating point with constant output given by $y(t) = y(w_o)$. Furthermore, the linearized closed-loop system at the constant operating point should be asymptotically stable with specified eigenvalues.

For each fixed $w_o$, the corresponding linearized closed-loop system with the nonlinear state feedback control law (3) can be written in the following form:

$$\begin{aligned} \dot{\boldsymbol{x}}_\delta(t) &= A(w_o)\boldsymbol{x}_\delta(t) + b(w_o)u_\delta(t), \\ y_\delta(t) &= C(w_o)\boldsymbol{x}_\delta(t), \\ u_\delta(t) &= K_1(w_o)\boldsymbol{x}_\delta(t) + K_2(w_o)w_\delta(t). \end{aligned} \tag{4}$$

Here, the deviation variables are defined by

$$\begin{aligned} \boldsymbol{x}_\delta(t) &= \boldsymbol{x}(t) - \boldsymbol{x}(w_o), \\ y_\delta(t) &= y(t) - r, \\ u_\delta(t) &= u(t) - u(w_o), \\ w_\delta(t) &= w(t) - w_o, \end{aligned} \tag{5}$$

while the linearized system coefficients are given by

$$\begin{aligned} A(w_o) &= \frac{\partial f(\boldsymbol{x}(w_o), u(w_o), w_o)}{\partial \boldsymbol{x}}, \\ b(w_o) &= \frac{\partial f(\boldsymbol{x}(w_o), u(w_o), w_o)}{\partial u}, \\ C(w_o) &= \frac{\partial h(\boldsymbol{x}(w_o))}{\partial \boldsymbol{x}}, \end{aligned} \tag{6}$$

and the linearized control law coefficients is obtained by

$$\begin{aligned} K_1(w_o) &= \frac{\partial k(\boldsymbol{x}(w_o), w_o)}{\partial \boldsymbol{x}}, \\ K_2(w_o) &= \frac{\partial k(\boldsymbol{x}(w_o), w_o)}{\partial w}. \end{aligned} \tag{7}$$

In order to achieve stability of the linearized closed-loop system, $K_1(w_o)$ is determined so that the eigenvalues of $A(w_o) + b(w_o)K_1(w_o)$ have specified values with negative real parts for each $w_o$. Then, one of the simplest in form can be obtained by a linear state feedback control law as the following (W. J. RUGH, 1995):

$$\begin{aligned} \bar{u}(t) &= k(\boldsymbol{x}(t), w(t)) \\ &= u(w_o) + K_1(w_o)(\boldsymbol{x} - \boldsymbol{x}(w_o)). \end{aligned} \tag{8}$$

Note, however, the system (1) has an uncertainty part. Therefore, we are going to eliminate the uncertainty part by means of a time-delay control technique while controlling the remnant part by using a gain scheduling method. Specifically, we propose a control method of time-delay-based gain scheduling, which is based on a direct estimation of a function representing the effect of uncertainty. The information from the estimation is used to cancel the unknown dynamics and unexpected disturbances simultaneously. In other words, the time-delay-based gain scheduled control utilizes the past observed response of the system with the control input to directly modify the control actions rather than adjusting the control gains.

Recalling the equation (2), we can express the uncertainty term as follows:

$$\Delta f(t) = \dot{x}_n(t) - f(\boldsymbol{x}(t), u(t), w(t)) \ . \tag{9}$$

Since the right-hand side terms of (9) are not available at the present time, we estimate the uncertainty term $\Delta f(t)$ based on the assumption that the value of the function $\Delta f(t)$ at the present time $t$ is very close to that at time $t-L$ in the past for a sufficiently small time delay $L$, that is, it is assumed that

$$\Delta f(t) \cong \Delta f(t-L) \ . \tag{10}$$

Then, from (9) and (10), the uncertainty term $\Delta f(t)$ can be estimated as [K. YOUCEF-TOUMI. AND O. ITO 1990]

$$\Delta \hat{f}(t) = \dot{x}_n(t-L) - f(\boldsymbol{x}(t-L), u(t-L), w(t-L)) \ . \tag{11}$$

Note that the system (1) satisfies a matching condition (K. YOUCEF-TOUMI *et al.* 1990), i.e., there exists some input to remove the effect of uncertainty. Therefore, we add the following exogenous input $\Delta u(t)$ to the control law (8).

$$\begin{aligned}\Delta u(t) &= -\frac{1}{b(w_o)}\Delta \hat{f}(t) \\ &= \frac{1}{b(w_o)}\{f(\boldsymbol{x}(t-L), u(t-L), w(t-L)) - \dot{x}_n(t-L)\}.\end{aligned} \tag{12}$$

where $b(w_o)$ is given in (7). Combing (8) and (9), we derive a Time-Delay-Based Gain Scheduled Controller ( TDGSC ) as follows:

$$u(t) = \bar{u}(t) + \Delta u(t)$$

$$\begin{aligned}u(t) &= \bar{u}(t) + \Delta u(t) \\ &= u(w_o) + K(w_o)(\boldsymbol{x} - \boldsymbol{x}(w_o)) + \frac{1}{b(w_o)}\{f(\boldsymbol{x}(t-L), u(t-L), w(t-L)) - \dot{x}_n(t-L)\}.\end{aligned} \tag{13}$$

In general, the scheduling variable $w(t)$ is not known in practical systems. Hence, it is necessary to estimate the scheduling variable $w(t)$. In order to determine an estimate of the scheduling variable, $\hat{w}(t)$, we rewrite the nonlinear dynamics (2) as follows:

$$f(\boldsymbol{x}(t), u(t), w(t)) = \dot{x}_n(t) - \Delta f(t) \ . \tag{14}$$

By using Taylor series expansion at $w(t) = w_o$, the left-hand part of (14) is described as

$$f(\boldsymbol{x}(t), u(t), w(t)) = f(\boldsymbol{x}(t), u(t), w_o) + \alpha\, w_\delta + o(w_\delta) \ , \tag{15}$$

Where $\alpha = \frac{\partial f(\boldsymbol{x}(t), u(t), w_o)}{\partial w(t)}$ is assumed to be a non-zero value. From (15), $w(t)$ can be described by

$$\begin{aligned}w(t) &= \alpha^{-1}\{f(\boldsymbol{x}(t), u(t), w(t)) - f(\boldsymbol{x}(t), u(t), w_o) - o(w_\delta)\} + w_o \\ &= \alpha^{-1}\{\dot{x}_n(t) - \Delta f(t) - f(\boldsymbol{x}(t), u(t), w_o) - o(w_\delta)\} + w_o,\end{aligned} \tag{16}$$

By substituting (11) into (16), the estimated scheduling variable $\hat{w}(t)$ can be approximated as

$$\begin{aligned}\hat{w}(t) &= \alpha^{-1}\{\dot{x}_n(t) - \Delta f(t-L) - f(\boldsymbol{x}(t), u(t), w_o)\} + w_o \\ &= \alpha^{-1}\{\dot{x}_n(t) - \dot{x}_n(t-L) + f(\boldsymbol{x}(t-L), u(t-L), w(t-L)) - f(\boldsymbol{x}(t), u(t), w_o)\} + w_o.\end{aligned} \tag{17}$$

Since $\hat{w}(t)$ is not available at present time $t$ for practical computation, we use $\hat{w}(t-L)$ at time $t-L$ in the past for a small time delay $L$. Here, $\hat{w}(t-L)$ is given by

$$\begin{aligned}&\hat{w}(t-L) \\ &\cong \alpha^{-1}\{\dot{x}_n(t-L) - \dot{x}_n(t-2L) + f(\boldsymbol{x}(t-2L), u(t-2L), \hat{w}(t-2L)) \\ &\qquad - f(\boldsymbol{x}(t-L), u(t-L), w_o)\} + w_o.\end{aligned} \tag{18}$$

Using the estimated scheduling variable in (18), we can rewrite the Time-Delay-Based Gain Scheduled Controller in (13) as follows:

$$u(t) = u(w_o) + K(w_o)(\boldsymbol{x} - \boldsymbol{x}(w_o)) + \frac{1}{b(w_o)}\{f(\boldsymbol{x}(t-L), u(t-L), \hat{w}(t-L)) - \dot{x}_n(t-L)\} \tag{19}$$

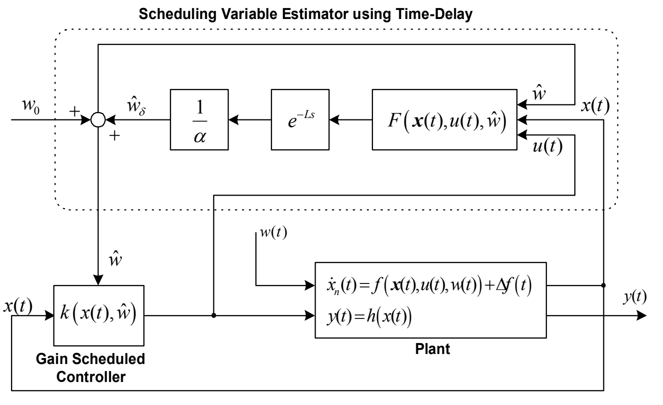


Figure 1: Block diagram of the time-delay-based gain sched-

Figure 1 shows the block diagram of the proposed control system. As shown in Figure 1, the estimated scheduling variable $\hat{w}$ is adapted to support the control law $u(t)$.

## 3 APPLICATION TO AN ELECTROMAGNETIC SUSPENSION SYSTEM AND SIMULATION

A serious problem of magnetically levitated transport systems is to cope with rail joints and rail irregularities. The rail joints and rail irregularities in the track of a railway system often cause instability of the magnetically levitated vehicle and tend to increase the regulation air-gap error at the levitated state.

Note that uncertainties such as air-gap disturbance and lifting force variation are dominant sources which deterioate the system performance. It is therefore very important to decrease the regulation air-gap error to guarantee safety and enhance ride quality of the railway systems.

As a possible application, we apply the proposed control method to an electromagnetic suspension system. Figure 2 shows the schematic diagram of a single magnet suspension system whose working principle may be found in (P. K. SINHA 1987).

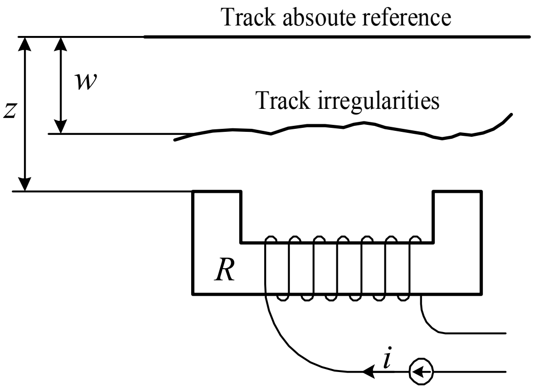


Figure 2: Configuration of a single magnet suspension system

The z-directional force dynamics of the magnet coil at the levitated state can be represented by

$$F(z(t),i(t)) = -\frac{\mu_0 N^2 A}{4}\left(\frac{i(t)}{z(t)-w(t)}\right)^2 + mg + \Delta f(t), \quad (20)$$

where $m$ is the total levitated mass, $N$ is the number of turns of the coil wrapped arround the magnet, $A$ is the effective magnet pole area, $\mu_0$ is the permeability of free space, $g$ is the gravity constant, $i(t)$ denotes the magnet current. $z(t)$ is the vertical air-gap displacement. $\Delta f(t)$ represents an uncertainty term caused by the lifting force variation of magnetically levitated transport system and the air-gap disturbance is scheduled by a scheduling variable $w(t)$ which satisfies $\|w(t)\| < \|z(t)\|$. From (20), the open-loop state equations of the levitation system can be given as follows:

$$\begin{aligned} \dot{x}_1(t) &= x_2(t), \\ \dot{x}_2(t) &= -\frac{\mu_0 N^2 A}{4m}\left(\frac{u(t)}{x_1(t)-w(t)}\right)^2 + g + \frac{1}{m}\Delta f(t), \\ y(t) &= x_1(t), \end{aligned} \quad (21)$$

where $x_1(t)$ and $x_2(t)$ is the vertical air-gap $z(t)$ and the vertical velocity $\dot{z}(t)$, respectively, while $u(t)$ denotes the magnet current $i(t)$ and $y(t)$ is the plant output.

To obtain the gain scheduled control law in (8), we compute the nominal state values, input, and output value for a constant $w_o$ under Assumption 1, which are given as follows:

$$\begin{aligned} \boldsymbol{x}(w_o) &= \begin{bmatrix} w_o + \frac{N}{2}\sqrt{\frac{\mu_0 A}{mg}}u(w_o) & 0 \end{bmatrix}^T, \\ u(w_o) &= \frac{2(r-w_o)}{N}\sqrt{\frac{mg}{\mu_0 A}}, \\ y(w_o) &= r. \end{aligned} \quad (22)$$

From (7), the linearized system coefficients at the nominal point in (20) are calculated as

$$\begin{aligned} \boldsymbol{A}(w_o) &= \begin{bmatrix} 0 & 1 \\ \frac{2g}{r-w_o} & 0 \end{bmatrix}, \\ b(w_o) &= \frac{N}{(w_o-r)}\sqrt{\frac{\mu_0 Ag}{m}}, \\ C(w_o) &= [1 \quad 0]. \end{aligned} \quad (23)$$

To satisfy a desired closed-loop dynamics whoes eigenvalues are specified by negative double root $\lambda^2 (\lambda > 0)$, we design the gain scheduling control input in (8) as follows:

$$\begin{aligned} \bar{u}(t) = {} & \frac{2(r-w_o)}{N}\sqrt{\frac{mg}{\mu_0 A}} + \frac{(r-w_o)}{N}\sqrt{\frac{m}{\mu_0 Ag}}(\lambda^2 + \frac{2g}{r-w_o})(x_1 - r) \\ & + \frac{2\lambda(r-w_o)}{N}\sqrt{\frac{m}{\mu_0 Ag}}x_2 \end{aligned} \quad (24)$$

where $u(w_o) = \frac{2(r-w_o)}{N}\sqrt{\frac{mg}{\mu_0 A}}$

and $K_1(w_o) = \begin{bmatrix} \frac{r-w_o}{N}\sqrt{\frac{m}{\mu_0 Ag}}\left(\lambda^2 + \frac{2g}{r-w_o}\right) & \frac{2\lambda(r-w_o)}{N}\sqrt{\frac{m}{\mu_0 Ag}} \end{bmatrix}.$

(25)

Furthermore, the estimated scheduling variable in (18) is obtained by

$$\begin{aligned} \hat{w}(t-L) \cong {} & \frac{w_o - r}{2g}\{\dot{x}_2(t-L) - \dot{x}_2(t-2L) + f(x(t-2L), u(t-2L), \hat{w}(t-2L)) \\ & - f(x(t-L), u(t-L), w_o)\} + w_o. \end{aligned} \quad (26)$$

Using (24) and (25), we obtain the TDGSC in (19) as follows:

$$\begin{aligned} u(t) = {} & \frac{2(r-w_o)}{N}\sqrt{\frac{mg}{\mu_0 A}} + \frac{(r-w_o)}{N}\sqrt{\frac{m}{\mu_0 Ag}}(\lambda^2 + \frac{2g}{r-w_o})(x_1(t) - r) + \frac{2\lambda(r-w_o)}{N} \\ & \sqrt{\frac{m}{\mu_0 Ag}}x_2(t) + \left[\frac{N}{(w_o-r)}\sqrt{\frac{\mu_0 Ag}{m}}\right]^{-1}\{f(\boldsymbol{x}(t-L), u(t-L), \hat{w}(t-L)) - \dot{x}_2(t-L)\}. \end{aligned} \quad (27)$$

To show the effectiveness of the proposed method, we compare the proposed method with a conventional State Feedback Controller (SFC) given by

$$u(t) = \frac{2r}{N}\sqrt{\frac{mg}{\mu_0 A}} + k_1(x_1(t) - r) + k_2 x_2(t) + k_3 \dot{x}_2(t), \quad (28)$$

where $k_1$, $k_2$ and $k_3$ are the feedback gains.

To illustrate the proposed control scheme under the air-gap disturbance and the lifting force variation of electromagnetic suspension system, we perform the simulations with the following information:

• for $F(z(t), i(t)) = -\frac{\mu_0 N^2 A}{4}\left(\frac{i(t)}{z(t) - w(t)}\right)^2 + mg + \Delta f(t)$, (29)

$\mu_0 = 4\pi \times 10^{-7}[H/m]$, $N = 660$, $A = 0.04[m^2]$, $g = 9.8[m/\sec^2]$;

• the air-gap disturbance $w(t)$ varies in a swept sinusoidal waveform or an irregular random noise;
• the variation of lifting force is given by $\Delta f(t) = m(0.1\sin 5t + 1)[N]$ with $m = 1000[kg]$;
• in the CSFC and TDGSC, the desired eigenvalues are specified by $\lambda_1 = \lambda_2 = -5.5$ and the time-delay $L$ is 0.001[sec];
• for the CSFC, the control gains are chosen to be $k_1 = 1000$, $k_2 = 100$, $k_3 = 1$ to satisfy the desired characteristics.

The simulations are carried out using MATLAB. Figure 3(a) and 4(a) shows the estimated air-gap disturbance, $\hat{w}(t)$, for the swept sinusoidal and random noise disturbances in the presence of lift force variation, respectively. Figure 3(b) and 4(b) shows the control results of both the TDGSC and the SFC, which are conducted by using the estimated air-gap disturbances. Obviously, the simulation results show that the SFC hardly reduces the effect of the air-gap disturbances and the lifting force variation, whereas the proposed TDGSC almost eliminates the effect of both the air-gap disturbances and the lifting force variation, and thus it shows better tracking performance.

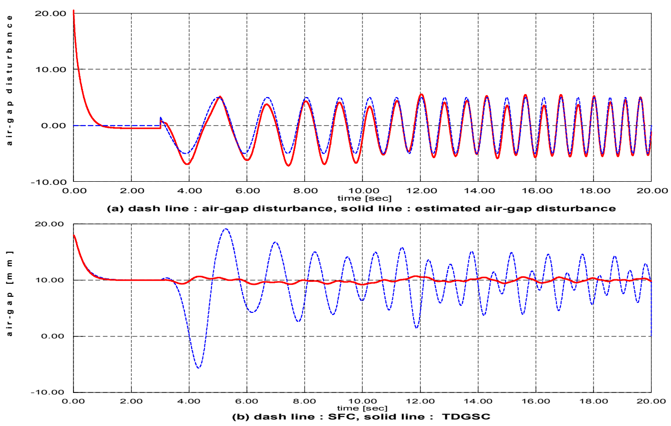


Figure 3: SFC and TDGSC against swept sinusoidal air-gap disturbance and lifting force variation

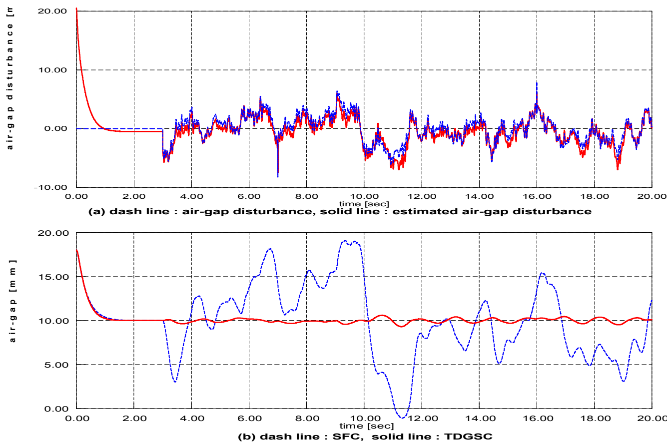


Figure 4: SFC and TDGSC against irregular random air-gap disturbance and lifting force variation

## 4 CONCLUDING REMARKS

A time-delay-based gain scheduled control of a class of nonlinear uncertain system is studied and applied for a electromagnetic suspension system model. The method is shown to be effective for the system not only with nonlinear plant uncertainty, but also with the property of open loop instability with air-gap disturbance. To remove the effect of undesirable disturbance, we scheduled the disturbance as a scheduling variable, which is estimated by using time-delay technique for practical implementation.

The benefits of this proposed controller are demonstrated via simulation of an electromagnetic suspension system with model uncertainty and external disturbances.

In the present paper, the design was restricted to a nonlinear SISO system in phase variable canonical form. To be practical, however, the method should be extended to MIMO system models, and be tested and validated by means of actual experiments involving a magnetically levitated vehicle. It is remarked that the study in the paper was originally motivated by experiences in a national project on "Development of a magnetically levitated vehicle System". As shown in Figure 5, an experimental vehicle has been developed by KIMM in Taejon, Korea, and is being under test for various simple control algorithms. For further studies, the authors wish that the results of the paper be tested for the actual experimental vehicle.

Figure 5: Photograph of experimental vehicle for magnetically levitated transport system


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