*ICIC Express Letters*
Volume **6**, Number **12**, December **2012**

ICIC International ©2012 ISSN 1881-803X
pp. 3149–3154

# A DIGITAL ACCELERATION CONTROLLER FOR AN ELEVATOR TO ADAPT TO LOAD CHANGES AND NONLINEAR AIR DAMPING

Yina Wang and Shuoyu Wang

School of Systems Engineering
Kochi University of Technology
185 Miyanokuchi, Tosayamada, Kami, Kochi 782-8502, Japan
156013z@gs.kochi-tech.ac.jp; wang.shuoyu@kochi-tech.ac.jp

Received August 2012; accepted November 2012

Abstract. *Elevator is widely used in our daily lives to carry passengers or transport belongings in the rising buildings. However, the motion performance of the elevator is strongly affected by load changes and nonlinear air damping. In this paper, to address these issues, the design of a digital acceleration control method is described. First, a dynamic model of an elevator is derived with consideration of load changes and nonlinear air damping. Then, a digital controller is designed based on the derived dynamics, and the parameter of the elevator is identified by using the control torque and the output acceleration signal. The digital acceleration controller is a special controller to deal with the load changes and nonlinear air damping for its control force contains the gravity force of the load and the nonlinear air damping. Finally, simulations are conducted, and the results demonstrate the effectiveness and usefulness of the proposed control method.*
**Keywords:** Elevator, Digital acceleration control, Load changes, Nonlinear air damping

1. **Introduction.** The heights of not only residential buildings but also commercial buildings have been increasing. As a type of vertical transport equipment for such high-rise buildings, the elevator is becoming more and more important in our daily lives to carry passengers or transport belongings between floors. To ensure comfort and convenience for passengers, the motion performance of the elevator must satisfy the goals of minimum flight time, minimum acceleration, accurate landing, and minimum vibration [1,2]. Therefore, a suitable controller is necessary.

Various researches on motion control of elevator have bas conducted, including robust control [3], time-optimal planning [4], and elevator group control [5]. The load, the elevator car, and the counterweight impose a gravity force on the elevator. As the load vary, significant changes of the gravity force lead to a serious external force disturbance on the elevator, and the system parameters are changed. The load changes thus have a serious effect on the motion performance of the elevator. Nonlinear air damping also has a serious effect on the motion performance of the elevator and very few articles have been published that specifically deal with nonlinear air damping issues. Therefore, if the problems of load changes and nonlinear air damping could be solved via control theory, the elevator's performance would significantly improve. We focus on the problem of load changes and nonlinear air damping to further improve the motion performance of an elevator.

One of the authors of [6] proposed a digital acceleration control method to specifically deal with nonlinear friction of a robot manipulator and this control method was experimentally validated in [7]. In our study, a control technique is designed on the basis of this method to compensate for load changes and nonlinear air damping of elevator. The control force of the digital acceleration controller contains the gravity force of the load and nonlinear air damping force by using the previous sampling period's control force and acceleration. In this way, this controller effectively deals with gravity force changes of the load and nonlinear air damping. In addition, the parameter of the elevator dynamic system is identified by using the previous control force and the obtained acceleration to compensate for the changing parameters.

This paper is organized as follows. First, a dynamic model of an elevator is derived by considering load changes and nonlinear air damping. Then, the digital acceleration controller is designed for this elevator to compensate for the load changes and the nonlinear air damping. In addition, the dynamic parameter is identified by using the previous control force and obtained acceleration. Finally, simulations are conducted. The results demonstrate the effectiveness and usefulness of the proposed control method.

2. **Modeling of the Elevator.** The elevator discussed in this paper is shown in Figure 1. The basic roped elevator dynamic system is illustrated in Figure 2. As shown, the elevator dynamic system consists of a drive motor, a drive pulley, an elevator car, and a counterweight. The elevator car and the counterweight are suspended from the drive pulley, which is driven by an electric motor.


FIGURE 1. The elevator

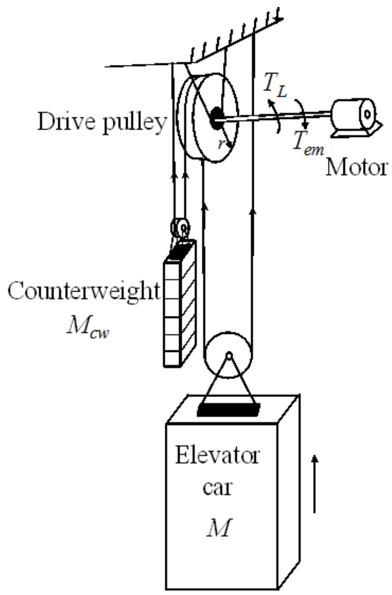


FIGURE 2. Structural model of the elevator

To derive the dynamic model for the elevator, firstly, the motion equation of the drive motor is given as follows:

$$\tau_{em} = J_M\ddot{\theta} + B\dot{\theta} + \tau_L \tag{1}$$

where $\tau_{em}$ is the electromagnetic torque of the drive motor, $J_M$ is the moment of inertia of the motor, $\theta$ is the angle of the motor, $B$ is the friction coefficient of the motor, and $\tau_L$ is the load torque placed on the motor shaft to drive the pulley.

Based on the dynamic system shown in Figure 2, the dynamic equation of the drive pulley, elevator car, and counterweight system is derived according with following assumptions: The hoist ropes of elevator car and counterweight are inextensible; The mass and the friction of the ropes and drive pulley are ignored; The direction of the load torque is set as clockwise and the moving direction of the elevator car is set as upward, as shown in Figure 2. Therefore, the dynamic equation of the drive pulley, elevator car, and counterweight system is given as follows:

$$\tau_L = \left[r^2\frac{(M+m-M_{cw})}{2} + J_P\right]\ddot{\theta} + r^2\frac{b}{2}\dot{\theta} + r^2\frac{c}{2}\dot{\theta}^2 + r\frac{(M+m-M_{cw})}{2}g \tag{2}$$

where $r$ is the radius of the drive pulley, $M$ is the mass of the elevator car, $m$ is the mass of the load, $M_{cw}$ is the mass of the counterweight, $J_P$ is the inertia of the drive pulley, $b$ is the viscous friction coefficient of the elevator car, $c$ is the damping coefficient of air, and $g$ is the gravitational constant. Substituting Equation (2) into the motor's motion Equation (1), the dynamic equation of the entire system is obtained as:

$$\tau_{em} = \left[r^2\frac{(M+m-M_{cw})}{2} + J_P + J_M\right]\ddot{\theta} + \left[r^2\frac{b}{2} + B\right]\dot{\theta} + r^2\frac{c}{2}\dot{\theta}^2 + r\frac{(M+m-M_{cw})}{2}g \tag{3}$$

The proposed controller is designed based on dynamic Equation (3) that the control variable is the motor angle $\theta$ controlled by the electromagnetic torque of motor $\tau_{em}$.

3. **Controller Design.** In this section, a digital acceleration controller is designed for the elevator. Firstly, the dynamic Equation (3) is rewritten as

$$J_0\ddot{\theta} + X[\theta,\dot{\theta}] = \tau_{em} \tag{4}$$

where

$$J_0 = \left[r^2\frac{(M+m-M_{cw})}{2} + J_P + J_M\right],$$

$$X[\theta,\dot{\theta}] = \left[r^2\frac{b}{2} + B\right]\dot{\theta} + r^2\frac{c}{2}\dot{\theta}^2 + r\frac{(M+m-M_{cw})}{2}g.$$

The control torque is kept constant between each time period of length $T$, as described in [6]. $T$ is the sampling interval of the control force, and $kT^+$ is set to be the instant after the change of the control torque at time $kT$. For the constant time periods $[(k-1)T^+, kT]$ and $[kT^+, (k+1)T]$, we obtain Equation (5) as

$$\begin{aligned} &J_0\ddot{\theta}(kT) + X[\theta(kT),\dot{\theta}(kT)] = \tau_{em}[(k-1)T^+] \\ &J_0\ddot{\theta}(kT^+) + X[\theta(kT^+),\dot{\theta}(kT^+)] = \tau_{em}(kT^+) \end{aligned} \tag{5}$$

where $\tau_{em}[(k-1)T^+] = \tau_{em}(kT)$ is the control force during $[(k-1)T^+, kT]$, and $\tau(kT^+)$ is the control force during $[kT^+, (k+1)T]$. When the control force changes from time $kT$ to $kT^+$, the acceleration is changed. However, the velocity, position, nonlinear friction and nonlinear air damping are still the same by the integral characteristic. Therefore, based on Equation (5), the control input is designed as follows:

$$\begin{aligned} \tau_{em}(kT^+) = &\tau_{em}[(k-1)T^+] + J_0\{[\ddot{\theta}_d(kT^+) - \ddot{\theta}(kT)] \\ &+ k_d[\dot{\theta}_d(kT) - \dot{\theta}(kT)] + k_p[\theta_d(kT) - \theta(kT)]\} \end{aligned} \tag{6}$$

where $k_d$ and $k_p$ are the speed deviation coefficient and the position deviation coefficient, respectively. Here, $k_d$ and $k_p$ are designed to verify the stability of the control system. From Equation (5) it is observed that the acceleration at time $kT$ contains the gravity force of the load and the nonlinear air damping force at time $kT$. Then, on the basis of control algorithm (6), the gravity force of the load and the nonlinear air damping force at time $kT$ are added via the acceleration to the control input at time $kT^+$. The gravity force of the load and the nonlinear air damping force at time $kT$ is the same as them at time $kT^+$. Therefore, it is effective for load change and nonlinear air damping.

Equation (6) shows that the design of the acceleration controller requires plant parameter $J_0$, which is a variable dependent on the load changes. In this paper, because the elevator system is only slowly time-varying, system parameter $J_0$ is assumed to be constant in every motion task. Therefore, the value of $J_0$ in controller is obtained by the following equation.

$$\hat{J}_0 = \frac{\tau_{em}(kT) - \tau_{em}[k(T-1)]}{\ddot{\theta}(kT) - \ddot{\theta}[k(T-1)]} \tag{7}$$

As shown in Equation (7), the parameter of the system is identified by the control torque input and the actual angular acceleration output.

4. **Simulation.** This section describes simulations conducted to verify the effectiveness and usefulness of the proposed controller to deal with load changes and nonlinear air damping. The physical parameters of the elevator used in the simulations are given as: $M = 900$ kg, $M_{cw} = 1300$ kg, $J_M = 1.98$ kg·m$^2$, $J_P = 4.38$ kg·m$^2$, $r = 0.38$ m, g =9.8 m/s$^2$, $B = 4.02$ N·m·s, $b = 2.4$ N·s/m, $c = 0.2$ N·s$^2$/m.

In the motion of the elevator, we look for a minimum time solution. However, the riding comfort of the passenger has an inverse relation with the acceleration of the elevator. The shorter the riding time is, the higher the acceleration is. In this paper, we consider the riding comfort and the riding time together to design a desired trajectory for the elevator in the simulations. The desired trajectory is based on the requirements shown in Table 1.

Table 1. Design requirements of desired trajectory

| Essential Element | Quantity | Desired Value |
|---|---|---|
| Riding comfort | Maximum acceleration | 0.9 m/s$^2$ |
| | Start shock and stop shock | Less than 0.1 m/s$^2$ |
| Riding time | Riding time for moving one floor (3.4 m) | 4.8 s |
| Landing error | Load changes and shifts | Within ±5 mm |

Based on Table 1, the desired trajectory is designed as follows:

$$\theta_d(t) = \begin{cases} \frac{A}{\omega}\left(t - \frac{1}{\omega}\sin\omega t\right), & t_1 \le t < t_2 \\ D_2 + \left(\frac{A}{\omega} - At_2\right)(t - t_2) + \frac{A}{2}(t^2 - t_2^2), & t_2 \le t < t_3 \\ D_3 + A\left(\frac{1}{\omega} + t_3 - t_2\right)(t - t_3) + \frac{A}{\omega^2}[1 - \cos\omega(t - t_3)], & t_3 \le t < t_4 \\ D_4 + A\left(t_3 - t_2 + \frac{1}{\omega}\right)(t - t_4) + \frac{A}{\omega^2}\sin\omega(t - t_4), & t_4 \le t < t_5 \\ D_5 + A\left(t_3 - t_2 + t_5 + \frac{1}{\omega}\right)(t - t_5) - \frac{A}{2}(t^2 - t_5^2), & t_5 \le t < t_6 \\ D_6 + \frac{A}{\omega}(t - t_6) + \frac{A}{\omega^2}[\cos\omega(t - t_6) - 1], & t_6 \le t \le t_7 \end{cases} \tag{8}$$

where

$$D_2 = \frac{A}{\omega}\left(t_2 - \frac{1}{\omega}\sin\omega t\right), \quad D_3 = D_2 + \left(\frac{A}{\omega} - At_2\right)(t_3 - t_2) + \frac{A}{2}(t_3^2 - t_2^2)$$

$$D_4 = D_3 + A\left(\frac{1}{\omega} + t_3 - t_2\right)(t_4 - t_3) + \frac{A}{\omega^2}[1 - \cos\omega(t_4 - t_3)],$$

$$D_5 = D_4 + A\left(t_3 - t_2 + \frac{1}{\omega}\right)(t_5 - t_4) + \frac{A}{\omega^2}\sin\omega(t_5 - t_4)$$

$$D_6 = D_5 + A\left(t_3 - t_2 + t_5 + \frac{1}{\omega}\right)(t_6 - t_5) - \frac{A}{2}(t_6^2 - t_5^2)$$

and where $A = 0.9/r = 2.37$ s$^{-2}$, $\omega = \pi/3$ s$^{-1}$, $t_1 = 0$ s, $t_2 = 1.5$ s, $t_3 = 3.5$ s, $t_4 = 5$ s, $t_5 = 6.5$ s, $t_6 = 8.5$ s, $t_7 = 10$ s.

The parameters of the proposed controller are adjusted in the simulation while the load and air damping are assumed to be zero. The obtained control parameters are given as $k_d = 3$ s$^{-1}$, $k_p = 0.6$ s$^{-2}$. Figures 3(1a)-3(1d) show the tracking performance and control torque of the elevator under the conditions that a load is not added ($m = 0$ kg)

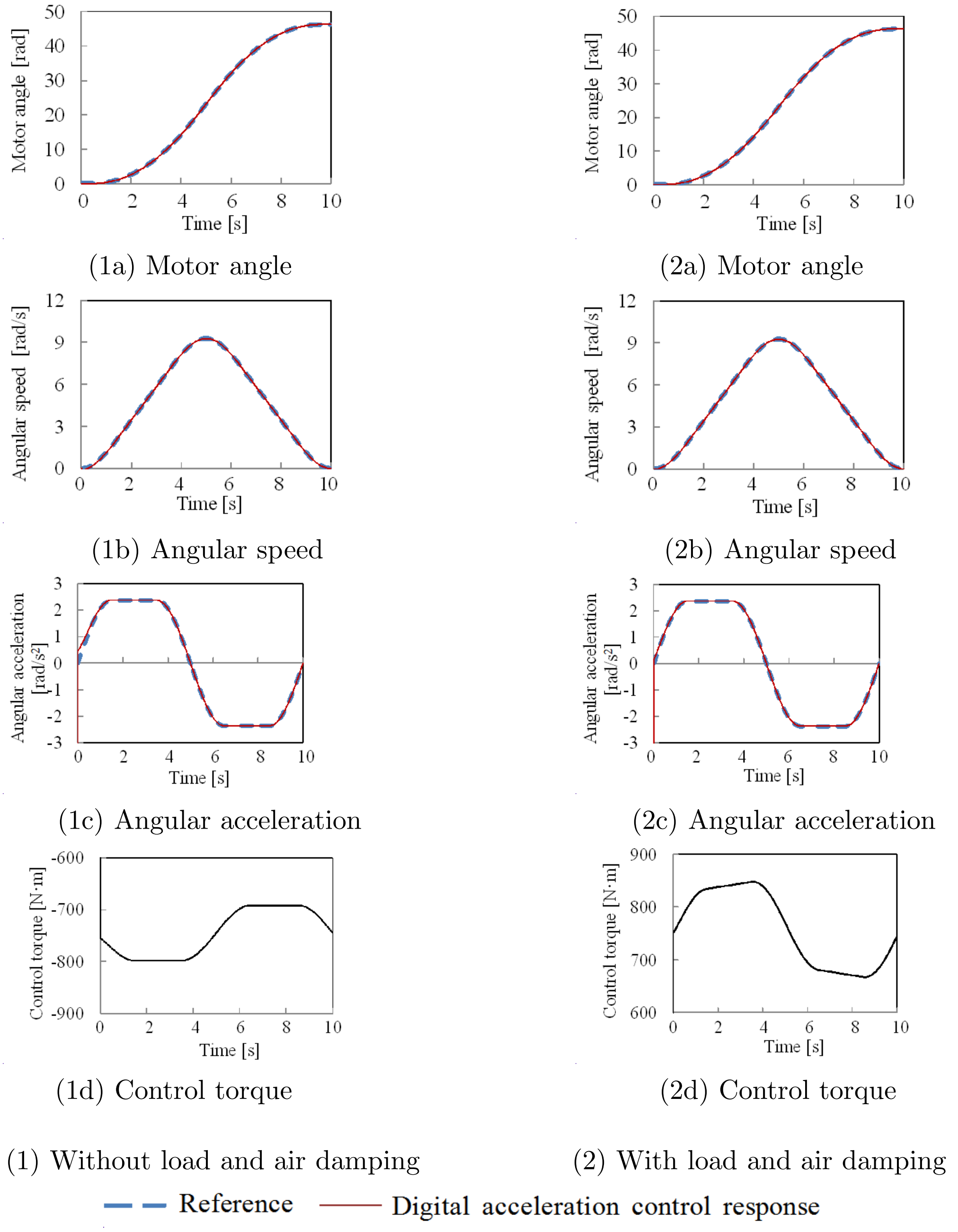


Figure 3. Simulation results using proposed control method

and nonlinear air damping is assumed to be zero. This is compared with Figures 3(2a)-3(2d), which show the tracking performance and control torque of the elevator under the conditions that a load is added ($m = 800$ kg) and nonlinear air damping is considered with no changes to the control parameters. In the comparison between Figures 3(1) and 3(2), the response curves of the tracking performance in Figures 3(2a)-3(2c) are similar to those in Figures 3(1a)-3(2c). These results indicate that the designed controller is useful to compensate for the effects of the load change and nonlinear air damping. In addition, the control torque in Figure 3(2d) has an obvious change form Figure 3(1d) according to the added load and air damping which indicate that this control force contains the gravity force of the load and air damping force.

The above simulation results show that the proposed control method is feasible and effective to the load change and nonlinear air damping. Using the proposed method, because the control torque of the previous sampling period includes the gravity force of the load and nonlinear air damping force, the current control torque could compensate for load change and nonlinear air damping based on the previous control torque.

5. **Conclusions.** In this paper, the design of a digital acceleration controller is described to improve the motion performance of an elevator. Simulations are performed and the results demonstrate the proposed controller effectively deals with load changes and nonlinear air damping. The future work will focus on the development of a new parameter identification method to further improve the motion performance of the elevator.

**Acknowledgment.** This study was supported by Grants-in-Aid for Scientific Research No. 23240088 and No. 22300197 from the Japan Society for the Promotion of Science.

## REFERENCES

[1] R. Roberts, Control of high-rise/high-speed elevators, *Proc. of the American Control Conference*, Philadelphia, PA, USA, pp.3440-3444, 1998.

[2] P. E. Utgoff and M. E. Connell, Real-time combinatorial optimization for elevator group dispatching, *IEEE Transactions on Systems, Man, and Cybernetics, Part A: Systems and Humans*, vol.42, no.1, pp.130-146, 2012.

[3] S. R. Venkatesh, Y. M. Cho and J. Kim, Robust control of vertical motions in ultra-high rise elevators, *Control Engineering Practice*, no.10, pp.121-132, 2002.

[4] M. Schlemmer and S. K. Agrewal, A computational approach for time-optimal planning of high-rise elevators, *IEEE Transactions on Control Systems Technology*, vol.10, no.1, pp.105-111, 2002.

[5] K. Hirasawa, T. Eguchi, J. Zhou, L. Yu, J. L. Hu and S. Markon, A double-deck elevator group supervisory control system using genetic network programming, *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, vol.38, no.4, pp.535-550, 2008.

[6] S. Y. Wang, T. Tsuchiya and Y. Hashimoto, The digital acceleration control method of robot manipulator, *Proc. of the 1st Symposium on Robot Robotics Society of Japan*, vol.1, pp.7-12, 1991 (in Japanese).

[7] S. Y. Wang, T. Tsuchiya and Y. Hashimoto, Path tracking control of robot manipulators utilizing future information of desired trajectory, *Transactions of the Japan Society of Mechanical Engineers*, vol.59, no.564C, pp.2512-2518, 1993 (in Japanese).