Springer

Journal of Mechanical Science and Technology 23 (2009) 3071~3078

Journal of
Mechanical
Science and
Technology

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-009-0912-4

Adaptive control of an axially moving system †

Quang Hieu Ngo[1], Keum-Shik Hong[2,*] and Il Hyo Jung[3]

[1]*School of Mechanical Engineering, Pusan National University, Busan 609-735, Korea*
[2]*Department of Cogno-Mechatronics Engineering, Pusan National University, Busan 609-735, Korea*
[3]*Department of Mathematics, Pusan National University, Busan 609-735, Korea*

(Manuscript Received May 16, 2009; Revised September 9, 2009; Accepted September 12, 2009)

Abstract

The objective of this paper is to move a load hanging under a very long rope from one place to another and to suppress the transverse vibrations of the load at the end of movement by adaptive control. The disturbance affecting the gantry motion is estimated and is incorporated into the control law design. The control command is given as a function of the position and velocity of the trolley, the hoisting speed, the sway angle of the rope at the gantry side, and the estimated disturbance force. The Lyapunov function taking the form of the total mechanical energy of the system is adopted to ensure the uniform stability of the closed-loop system. Through experiments, the effectiveness of the proposed control law is demonstrated.

Keywords: Axially moving system; Adaptive control; Boundary control; Container crane; Sway suppression; Transverse vibration; Lyapunov method

1. Introduction

Cranes are widely used to transport loads from one place to another in various areas: ports, warehouses, factories, construction sites, nuclear facilities, and others. Since the movement of the trolley sways the load during its movement, the main issue in a crane system is the quick suppression of vibrations caused by the trolley motion. In addition, a residual sway occurs at the end of the trolley movement due to crane dynamics and disturbances like winds. Thus, researchers working in the area of crane control have always targeted sway suppression.

In modeling crane dynamics, two approaches are used. The first approach is the lumped-mass approach, in which the hoisting rope is modeled as a mass-less rigid rod and the payload is modeled as a lumped point mass. The sway motion is modeled as a pendulum motion in two or three dimensional space. Therefore, an ordinary differential equation (ODE) model is used in deriving the control laws. Numerous papers on crane control using this approach have appeared in the literature [1-14]. Another approach is the distributed parameter system approach, in which the hoisting rope is considered as a string (distributed-mass). A typical assumption in the second approach is that the rope is perfectly flexible and inextensible. In this case, the dynamics of the crane system is expressed as a coupled ODE and partial differential equation (PDE): the trolley motion is given in the ODE form and the rope dynamics is given in the PDE form [15-19]. By using the PDE form, the payload as well as the rope motion is described exactly, especially when the rope length is very large and the payload is very heavy. In addition, the vibration of the rope that affects the payload motion during the trolley movement is also more accurately suppressed, expecially, when it is considered as the flexible system [20-24].

Sway suppression using a PDE model has been

† This paper was recommended for publication in revised form by Associate Editor Shuzhi Sam Ge
*Corresponding author. Tel.: +82 51 510 2454, Fax.: +82 51 514 0685
E-mail address: kshong@pusan.ac.kr

investigated recently. Rahn et al. [15] developed a proportional, derivative, and coupling amplification control law using a flexible cable model. A root locus analysis based on Galerkin's method for tuning control gains was another interesting feature of their work. d'Andrea-Novel et al. [16] developed a hybrid ODE-PDE model for overhead cranes and provided the asymptotic stability of a closed-loop system under the assumption that the rope length was constant. In [17], they also established the uniform exponential stability of the closed-loop system of their original problem by adding an angular-velocity feedback of the rope in addition to the displacement feedback, the velocity of the trolley and the angular-displacement of the rope. In [18], d'Andrea-Novel and Coron proposed a torque control to stabilize an overhead crane with a variable-length flexible cable. On the other hand, Kim et al. [19] modeled a container crane as an axially moving string system and proposed a boundary control law utilizing the hoisting speed as well as the sway angle of the rope. In their work, the Lyapunov function approach was adopted in ensuring stability.

In this paper, an axially moving string model for container cranes with changing the rope length is firstly introduced [19]. Considering the variation of the rope length and the disturbance effect on the gantry motion, an adaptive control law is derived, in which the disturbance as rail friction, frame vibration, etc, is estimated. When the load is hoisted arbitrarily, the uniform stability of the closed-loop system with the proposed control law is proven by a properly chosen Lyapunov function. The control performance was improved by the derived control law from that achieved by a few representative control algorithms in the literature, as demonstrated with experimental results.

The paper is structured as follows. In Section 2, the equations of motion of a container crane, modeled as an axially moving string, are briefly discussed by using the extended Hamilton's principle for systems with changing mass. In Section 3, an adaptive control scheme that suppresses the transverse vibrations to guarantee the stability of the crane system is presented. In Section 4, experiments are performed to verify the effectiveness of the designed control law. In Section 5, conclusions are provided.

2. Equations of motion

Fig. 1 shows the schematic diagram of a typical rope-driven-type container crane consisting of the trolley (gantry), the hoisting rope, and the spreader including a payload. The payload is grabbed by the spreader and they are hung from the gantry by a flexible rope having length $l(t)$, and mass density ρ kg/m. The rope is assumed to be perfectly elastic, is assumed to offer no resistance to bending, and has negligible extension from the static equilibrium state (owing to the load) due to sway. The transverse vibration $w(x,t)$ of the rope depends on both the spatial variable x and time t. The masses of the gantry and the payload are m_g and m, respectively. A control force $f_g(t)$ is applied to the gantry, and the gantry is affected by disturbance force $d(t)$. The trolley movement to its target position gives rise to the lateral vibrations of the rope (due to flexibility) as well as the sway motion of the spreader. In an actual crane, four ropes are used to hoist the spreader (payload). But, for simplicity, the use of one rope is modeled in this paper. The dynamics of the hoisting rope is modeled as an axially-moving string system. It is assumed that the motions of both the spreader and the rope occur in a vertical plane, that is, the X-Y plane in Fig. 1.

Let t be the time, x be the spatial coordinate in the X-axis, g be the gravitational acceleration, and $P(x, t)$ be the tension along the rope caused by the weight of the rope as well as that of the payload. The tension is, therefore, spatially-varying. By assuming that the sway angle is relatively small, the tension along the rope is simplified as follows [25].

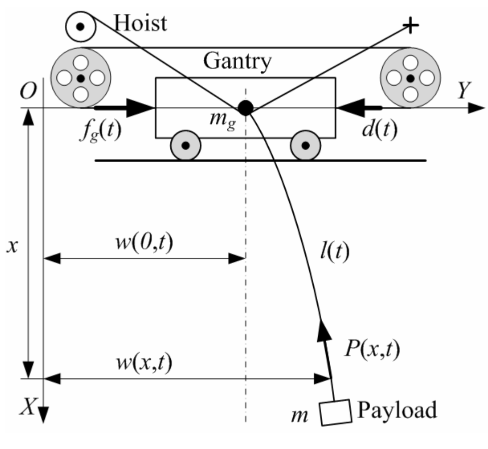


Fig. 1. Schematic of a container crane system.

$$P(x,t) \cong (m + \rho(l(t) - x))(g - \ddot{l}(t)). \quad (1)$$

For notational convenience, P, w, and l will be used instead of $P\ (x,t)$, $w\ (x,\ t)$, and $l\ (t)$, by omitting the independent variables x and t.

The potential energy of the crane system due to transverse rope displacements is given as follows.

$$U = \frac{1}{2}\int_0^l P w_x^2\, dx\,. \quad (2)$$

The kinetic energy of the entire crane system is given by

$$T = \frac{1}{2} m_g w_t^2(0,t) + \frac{1}{2}\rho\int_0^l \left\{\dot{l}^2 + \left(w_t + \dot{l} w_x\right)^2\right\} dx + \frac{1}{2} m\left\{\dot{l}^2 + \left(w_t(l,t) + w_x(l,t)\right)^2\right\}, \quad (3)$$

where the first, second, and third terms are the kinetic energies of the gantry, the rope, and the payload, respectively. It is noted that the second term includes the axially translating kinetic energy of the rope due to hoisting (i.e., $\dot{l}^2$ terms) as well as the transversal vibration energy of the rope (i.e., $(w_t + \dot{l} w_x)^2$ terms). Because the rope length $l\ (t)$ changes with time, the domain of integration in (3) for spatial variable x is time-dependent. The work done by the control force $f_g\ (t)$ and disturbance force $d\ (t)$ is given by

$$W = \left(f_g(t) - d(t)\right) w(0,t)\,. \quad (4)$$

For (2)-(4), the application of the extended Hamilton's principle, i.e.,

$$\int_{t_1}^{t_2} \left(\delta T - \delta U + \delta W\right) dt = 0\,, \quad (5)$$

yields the system equation as

$$\rho\left(w_{tt} + 2\dot{l} w_{xt} + \ddot{l} w_x + \dot{l}^2 w_{xx}\right) - \left(P w_x\right)_x = 0\,,\ 0 < x < l\,, \quad (6)$$

and the boundary conditions as

$$m_g\, w_{tt} + \rho\, \dot{l}\left(w_t + \dot{l} w_x\right) - P w_x + d(t) = f_g(t)\,,\ \text{at } x = 0, \quad (7)$$

$$m\left(w_{tt} + 2\dot{l} w_{xt} + \ddot{l} w_x + \dot{l}^2 w_{xx}\right) + P w_x = 0\,,\ \text{at } x = l, \quad (8)$$

where (7) and (8) are the dynamics of the gantry and the payload, respectively.

3. Control law design

Control objectives in this paper are, first, to move the load to a desired position w_d, which is normally given as a fixed value, and second, to suppress the payload transverse vibration to zero when the gantry reaches the target position. The disturbance cannot be measured, so it is estimated. Assuming that the magnitude of the disturbance $d(t)$ is μ_d, where μ_d is an unknown positive constant. The direction of the disturbance is opposite to that of the trolley velocity and it can be given as $d(t) = -\mathrm{sgn}(w_t(0,t))\mu_d$.

Theorem: Consider the plant (6)-(8). The control law

$$f_g = -k_1\left(w(0,t) - w_d\right) - k_2 w_t(0,t) + \rho\dot{l}\left(w_t(0,t) + \dot{l} w_x(0,t)\right) + (\alpha - 1)P(0,t) w_x(0,t) + \alpha\dot{l} P(0,t)\frac{w_x^2(0,t)}{\left(w_t(0,t) + \sigma_0\right)} - \mathrm{sgn}\left(w_t(0,t)\right)\hat{\mu}_d \quad (9)$$

and the adaptive law

$$\dot{\hat{\mu}}_d = -\gamma_d\, \mathrm{sgn}\left(w_t(0,t)\right) w_t(0,t) \quad (10)$$

guarantee the uniformly stability of the closed-loop system, and ensure that $w(0,t) \to w_d$ as $t \to \infty$, where k_1, k_2, α, and γ_d are positive constants, $\hat{\mu}_d$ is the adaptive estimate of μ_d, and

$$\sigma_0 = \begin{cases} \mathrm{sgn}\left(\dot{l} w_t(0,t)\right)\left|w_t(0,t)\right|/2, & \text{if } w_t(0,t) \neq 0 \\ \delta_0, & \text{if } w_t(0,t) = 0 \end{cases} \quad (11)$$

where δ_0 is a positive constant.

Proof: The Lyapunov function method, which eventually guarantees the uniform stability of the closed-loop system, is adopted. First, the positive function, in the form of the total mechanical energy of the system, is considered as follows.

$$V(t) = \frac{1}{2}\alpha\int_0^l \left\{\rho\left(w_t + \dot{l} w_x\right)^2 + P(x,t) w_x^2\right\} dx + \frac{1}{2} m_g w_t^2(0,t) + \frac{1}{2} k_1\left(w(0,t) - w_d\right)^2 + \frac{1}{2}\alpha\, m\left(w_t(l,t) + \dot{l} w_x(l,t)\right)^2 + \frac{1}{2\gamma_d}\tilde{\mu}^2\,, \quad (12)$$

where $\tilde{\mu} = \hat{\mu} - \mu$. The time derivative of (12) is calculated as follows.

$$\dot{V}(t) = -\alpha(\dddot{l}/2)\int_0^l \{m + \rho(l(t) - x)\} w_x^2 \, dx$$
$$-\alpha \dot{l} P w_x^2\Big|_{x=0} + \frac{\tilde{\mu}\dot{\hat{\mu}}}{\gamma_d} + w_t\{f_g - d(t) - (\alpha-1)Pw_x$$
$$-\rho\dot{l}(w_t + \dot{l}w_x) + k_1(w - w_d)\}\Big|_{x=0} . \quad (13)$$

where $d(t) = -\mathrm{sgn}(w_t(0,t))\mu_d$. A jerk $\dddot{l}(t)$ in the first term generates either a stabilizing or a destabilizing effect. In this paper, the hoisting rope length $l(t)$ is treated as a second-order polynomial in time, thus $\dddot{l}(t) = 0$. During extension $(\dot{l} > 0)$ or retraction $(\dot{l} < 0)$, the second term in (12) is a negative or positive value corresponding to the decrease or increase of the vibration energy and also generates either the stabilizing or the destabilizing effect. However, the destabilizing effect can be suppressed by making the third term sufficiently large [25].

The substitution of (9) into (13) yields

$$\dot{V}(t) = \frac{1}{\gamma_d}\left(\dot{\hat{\mu}}_d - \gamma_d \,\mathrm{sgn}(w_t(0,t)) w_t(0,t)\right)\tilde{\mu}_d$$
$$-\alpha(1 - w_t/(w_t + \sigma_0))\dot{l}Pw_x^2\Big|_{x=0} - k_2 w_t^2(0,t) . \quad (14)$$

Applying the adaptive law (10) to (14), Eq. (14) becomes

$$\dot{V}(t) = -\alpha(1 - w_t/(w_t + \sigma_0))\dot{l}Pw_x^2\Big|_{x=0}$$
$$-k_2 w_t^2(0,t) \le 0 . \quad (15)$$

It is noted that $(1 - w_t(0,t)/(w_t(0,t) + \sigma_0))\dot{l}$ in the first term is always positive by the definition of σ_0 (11); then, (15) ensures the uniform stability. The proof is completed.

Remark: Note that if $\dot{l} = 0$, the material derivative can be replaced by partial derivative and (13) becomes

$$\dot{V}(t) = w_t\{f_g + d - (\alpha-1)Pw_x + k_1(w - w_d)\}\Big|_{x=0}$$
$$+\frac{\tilde{\mu}\dot{\hat{\mu}}}{\gamma_d} . \quad (16)$$

And the proposed control law (9) can be reduced as follows.

$$f_g = -k_1(w(0,t) - w_d) - k_2 w_t(0,t)$$
$$+(\alpha-1)P(0,t)w_x(0,t) - \mathrm{sgn}(w_t(0,t))\hat{\mu}_d . \quad (17)$$

4. Experimental verification

In an experiment, the InTeCo 3DCrane (Poland) was used, whose the mass per unit length of the rope and the mass of the payload were $\rho = 0.01$ kg/m and $m = 0.73$ kg, respectively. This control law is compared with that of Rahn et al. [15] and a well-tuned PD controller, for verification. The experiment consisted of the gantry transport from 0.2 m to 1.5 m and up/down hoisting of the payload from 0.4 m to 1 m. The sway angle of the rope was a comparison criterion.

4.1 Rahn's control law

The proposed control law in [15] for a flexible cable gantry crane is given as follows.

$$f_g(t) = -K_1(w(0,t) - w_d) - K_2 w_t(0,t) + K_3 w_x(0,t), \quad (18)$$

where K_1, K_2 and K_3 are the control gains: They are set to 10, 3 and 12, respectively, in this experiment.

4.2 PD controller

The conventional PD controller is given by

$$f_g(t) = k_p\, e(t) + k_d\, \dot{e}(t) + k_a\, \theta(t), \quad (19)$$

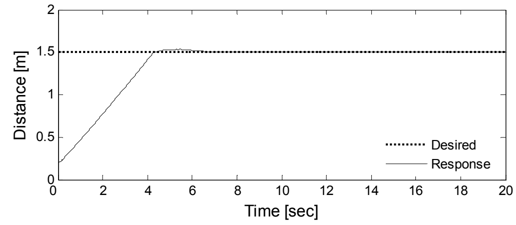
where k_p, k_d and k_a are the proportional and derivative gains associated with the trolley position and the sway angle in suppressing the vibrations of the load and $e(t) = w_d - w(0,t)$ and $\theta(t)$ are the position error and the sway angle, respectively. After numerous trials, the parameters of the PD controller are set to $k_p = 10$, $k_d = 3$, and $k_a = 12$.

4.3 The proposed adaptive control law

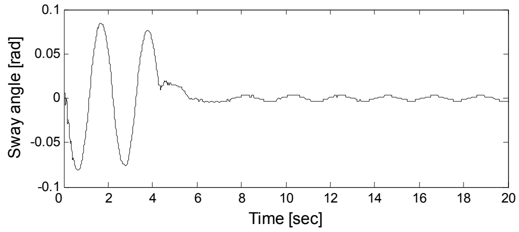
The proposed adaptive control law is given in (9). The disturbance can be estimated by using the adaptive law (10).

4.4 Results and discussion

Fig. 2 presents the response of (9) with $k_1 = 5$, $k_2 = 5$, $\alpha = 3$ and $\delta_0 = 1$ when the gantry travels from 0.2 m to 1.5 m and the rope length is 1 m (constant). In the case of a constant rope length, as seen in Fig. 2(b), the sway angle reduces to zero imm-



(a) Trolley position



(b) Sway angle

Fig. 2. Control performance with the proposed control law (9): The rope length is constant (1 m).

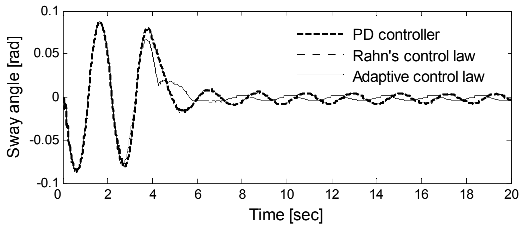
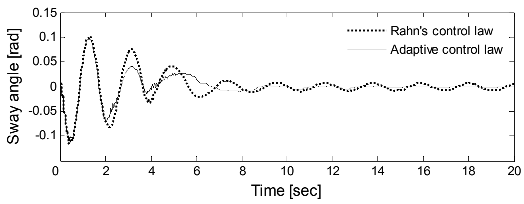
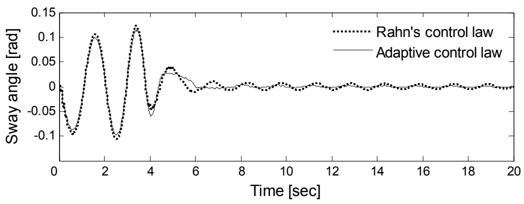


Fig. 3. Comparison of (9), (18), and (19) using the same experimental set up: The gantry travels from 0.2 m to 1.5 m and the rope length is constant (1 m).

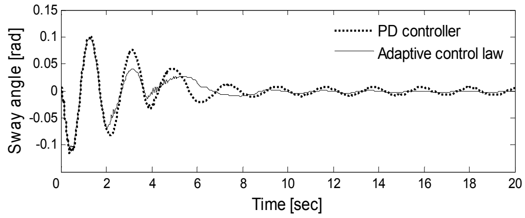


(a) Extension the rope from 0.4 m to 1.0 m

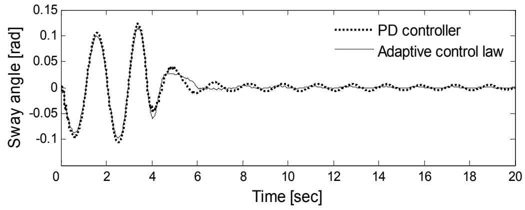


(b) Shortening the rope from 1.0 m to 0.4 m

Fig. 4. Comparison of (9) and (18): When the rope length was extended, the amplitude at the second peak was improved by 40 %.



(a) Extension the rope from 0.4 m to 1.0 m



(b) Shortening the rope from 1.0 m to 0.4 m

Fig. 5. Comparison of (9) and (19): With the estimation of the friction, the sway angle was further reduced.

ediately when the gantry reaches the target position. The position of the trolley has a small and acceptable overshoot. In this experiment (constant rope length), the control performance of the proposed control law showed no difference from those of Rahn's control law and the PD controller, as shown in Fig. 3.

Fig. 4 compares the sway angle of the proposed control law (9) with that of (18) for the rope length changing from 0.4 m to 1.0 m. The amplitude of the sway angle (at the second peak, they are 0.75 radian and 0.4 radian, respectively) was improved by 40% during the extension process. As shown in Fig. 5, the same conclusion can be drawn from the comparison of the adaptive control law with the PD controller (19) under the same experimental conditions.

5. Conclusions

In this paper, an adaptive boundary control for container cranes from the perspective of controlling an axially moving system with arbitrary rope length was presented. The consideration of cranes as an axially moving system [26-36] has become appropriate as cranes have become larger to deal with mega-size container ships. In this study, the proposed control law was applied to only a pilot crane to show its ability to improve sway suppression, but if it is applied to a crane with a very long rope, it will show an even higher control performance.

Acknowledgment

This work was supported by the National Research Foundation of Korea (grant no. KRF-2007-314-D00011) and by the Regional Research Universities Program/Institute of Logistics Information Technology.

References

[1] D. Liu, J. Yi, D. Zhao and W. Wang, Adaptive sliding mode fuzzy control for a two-dimensional overhead crane, *Mechatronics* 15 (5) (2005) 505-512.

[2] G. Bartolini, A. Pisano and E. Usai, Second-order sliding-mode control of container cranes, *Automatica* 38 (10) (2002) 1783-1790.

[3] H. H. Lee, Y. Liang and D. Segura, A sliding-mode anti-swing trajectory control for overhead cranes with high-speed load hoisting, *ASME Journal of Dynamic Systems, Measurement, and Control* 128 (4) (2006) 842-845.

[4] H. Park, D. Chwa and K. S. Hong, A Feedback linearization control of container cranes: varying rope length, *International Journal of Control, Automation, and Systems* 5 (4) (2007) 379-387.

[5] J. W. Auernig and H. Troger, Time optimal control of overhead cranes with hoisting of the load, *Automatica* 23 (4) (1987) 437-447.

[6] K. A. F. Moustafa and A. M. Ebeid, Nonlinear modeling and control of overhead crane load sway, *ASME Journal of Dynamic Systems, Measurement, and Control* 110 (3) (1988), 266-271.

[7] Y. Sakawa and Y. Shindo, Optimal control of container cranes, *Automatica* 18 (3) (1982) 257-266.

[8] Y. J. Hua and Y. K. Shine, Adaptive coupling control for overhead crane systems, *Mechatronics* 17 (2-3) (2007) 143-152.

[9] Y. Fang, W. E. Dixon, D. M. Dawson and E. Zergeroglu, Nonlinear coupling control laws for an underactuated overhead crane system, *IEEE/ASME Transactions on Mechatronics* 8 (3) (2003) 418-423.

[10] Z. N. Masoud and A. H. Nayfeh, Sway reduction on container cranes using delayed feedback controller, *Nonlinear Dynamics* 34 (3-4) (2003) 347-358.

[11] Y. S. Kim, K. S. Hong and S. K. Sul, Anti-sway control of container cranes: inclinometer, observer, and state feedback, *International Journal of Control, Automation, and Systems* 2 (4) (2004) 435-449.

[12] K. S. Hong, B. J. Park and M. H. Lee, Two-stage control for container cranes, *JSME International Journal, Series C* 43 (2) (2000) 273-282.

[13] H. C. Cho and K. S. Lee, Adaptive control and stability analysis of nonlinear crane systems with perturbation, *Journal of Mechanical Science and Technology* 22 (6) (2008) 1091-1098.

[14] K. T. Hong, C. D. Huh and K. S. Hong, Command shaping control for limiting the transient sway angle of crane systems, *International Journal of Control, Automation, and Systems* 1 (1) (2003) 43-53.

[15] C. D. Rahn, F. Zhang, S. Joshi and D. M. Dawson, Asymptotically stabilizing angle feedback for a flexible cable gantry crane, *ASME Journal of Dynamic Systems, Measurement, and Control* 121 (3) (1999) 563-566.

[16] B. d'Andréa-Novel, F. Boustany, F. Conrad and B. P. Rao, Feedback stabilization of a hybrid PDE-ODE system: application to an overhead crane, *Math. Control Signals Systems* 7 (1) (1994) 1-22.

[17] B. d'Andrea-Novel, B. and J. M. Coron, Exponential stabilization of an overhead crane with flexible cable via a back-stepping approach, *Automatica* 36 (4) (2000) 587-593.

[18] B. d'Andréa-Novel and J. M. Coron, Stabilization of an overhead crane with a variable length flexible cable, *Computational and Applied Mathematics* 21 (1) (2002) 101-134.

[19] C. S. Kim and K. S. Hong, Boundary control of container cranes from perspective of controlling an axially moving string system, *International Journal of Control, Automation, and Systems* 7 (3) (2009) 437-445.

[20] J. Park and N. Kang, Applications of fiber models based on discrete element method to string vibration, *Journal of Mechanical Science and Technology* 23 (2) (2009) 372-380.

[21] J. H. Park and S. Rhim, Experiments of optimal delay extraction algorithm using adaptive time-delay filter for improved vibration suppression, *Journal of Mechanical Science and Technology* 23 (4) (2009) 997-1000.

[22] J. W. Yoon, T. W. Park, S. H. Lee, K. J. Jun and S. P. Jung, Synthetic analysis of flexible multibody system including a very flexible body, *Journal of Mechanical Science and Technology* 23 (4) (2009) 942-945.

[23] K. T. Lee, Vibration of two cantilever beams clamped at one end and connected by a rigid body at the other, *Journal of Mechanical Science and*

Technology 23 (2) (2009) 358-371.

[24] H. C. Cho, J. W. Lee, Y. J. Lee and K. S. Lee, Lyapunov theory based robust control of complicated nonlinear mechanical systems with uncertainty, *Journal of Mechanical Science and Technology* 22 (11) (2008) 2142-2150.

[25] W. D. Zhu and J. Ni, J. Huang, Active control of translating media with arbitrarily varying length, *ASME Journal of Vibration and Acoustics* 123 (3) (2001) 347-358.

[26] J. Y. Choi, K. S. Hong and K. J. Yang, Exponential stabilization of an axially moving tensioned strip by passive damping and boundary control, *Journal of Vibration and Control* 10 (5) (2004) 661-682.

[27] K. J. Yang, K. S. Hong and F. Matsuno, Robust adaptive boundary control of an axially moving string under a spatiotemporally varying tension, *Journal of Sound and Vibration* 273 (4-5) (2004) 1007-1029.

[28] K. J. Yang, K. S. Hong and F. Matsuno, Energy-based control of axially translating beams: varying tension, varying speed, and disturbance adaptation, *IEEE Trans. on Control Systems Technology* 13 (6) (2005) 1045-1054.

[29] C. W. Kim, K. S. Hong and H. Park, Boundary control of an axially moving string: actuator dynamics included, *Journal of Mechanical Science and Technology* 19 (2005) 40-50.

[30] C. W. Kim, H. Park and K. S. Hong, Boundary control of axially moving continua: application to a zinc galvanizing line, *International Journal of Control, Automation, and Systems* 3 (2005) 601-611.

[31] K. J. Yang, K. S. Hong and F. Matsuno, Energy-based control of axially translating beams: varying tension, varying speed, and disturbance adaptation, *IEEE Trans. on Control Systems Technology* 13 (2005) 1045-1054.

[32] K. J. Yang, K. S. Hong and F. Matsuno, Robust boundary control of an axially moving string by using a PR transfer function, *IEEE Trans. on Automatic Control* 50 (2005) 2053-2058.

[33] K. J. Yang, K. S. Hong and F. Matsuno, Boundary control of an axially moving steel strip under a spatiotemporally varying tension, *JSME International Journal, Series C* 47 (2) (2004) 665-674.

[34] K. J. Yang, K, S. Hong and F. Matsuno, Boundary control of a translating tensioned beam with varying speed, *IEEE/ASME Transactions on Mechatronics* 10 (5) (2005) 594-597.

[35] K. S. Hong, C. W. Kim and K. T. Hong, Boundary control of an axially moving belt system in a thin-metal production line, *International Journal of Control, Automation, and Systems* 1 (2004) pp. 55-67.

[36] K. J. Yang, K. S. Hong and F. Matsuno, Robust adaptive boundary control of an axially moving string under a spatiotemporally varying tension, *Journal of Sound and Vibration* 273 (2004) 1007-1029.

Quang Hieu Ngo received the B.S. degree in mechanical engineering from Ho Chi Minh City University of Technology, Vietnam, in 2002, the M.S. degree in mechatronics from Asian Institute of Technology, Thailand, in 2007. He is currently a Ph.D. candidate in the School of Mechanical Engineering, Pusan National University, Korea. His research interests include port automation, control of axially moving systems, adaptive control, and input shaping control.

Keum Shik Hong received the B.S. degree in mechanical design and production engineering from Seoul National University in 1979, the M.S. degree in ME from Columbia University in 1987, and both the M.S. degree in applied mathematics and the Ph.D. degree in ME from the University of Illinois at Urbana-Champaign in 1991. Dr. Hong serves as Editor-in-Chief of the *Journal of Mechanical Science and Technology*. He served as an Associate Editor for *Automatica* (2000-2006) and as an Editor for the *International Journal of Control, Automation, and Systems* (2003-2005). Dr. Hong received Fumio Harashima Mechatronics Award in 2003 and the Korean Government Presidential Award in 2007. His research interests include nonlinear systems theory, adaptive control, distributed parameter system control, robotics, and vehicle controls.

Il Hyo Jung received the B.S. degree in mathematics from Pusan National University, Korea, in 1991, the M.S. and Ph.D. degrees in applied mathematics from KAIST, Korea, in 1993 and 1997, respectively. Dr. Jung is currently Associate Professor in the Department of Mathematics, Pusan Nation University, Korea. His research interests include differential equations (ODE/PDE), stability analysis, systems theory, and optimal control problems.