New Elevator Speed Control Technology Adopting ILQ Theory

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Abstract

It is important to reduce vertical vibration to establish riding comfort. There are two main difficulties in designing a speed controller.

. Rope resonance frequency varies with car position and load. This is especially notable in high rise elevators.

. In hydraulic elevators, there is another resonance frequency, due to oil compression. This affects cage speed control performance.

Inverse linear quadratic (ILQ) design theory is applied to develop a new speed controller in order to minimize cage vibration. ILQ controllers for both rope and hydraulic elevators are designed. These controllers make it easy to optimize the controller parameters because the control law obtained is represented as a function of plant parameters. A simulator is used to evaluate controller performance. Experimental results confirm its excellent vibration damping performance.

1. ILQ design theory

ILQ design theory is known as a practical design method for servo systems, which is derived from the viewpoint of the Inverse Regulator Problem. It has several features.

a) It enables us to design a control law directly using a desired speed control response.

b) A specified transfer function can be achieved asymptotically by increasing a particular design parameter Σ called a "tuning parameter."

c) It always has a +/- 60-degree phase margin, an infinite gain margin, and a 50 percent gain reduction tolerance sheared by all LQ regulators.

Consider a controllable, observable and minimum phase system:

$$\begin{cases} \dfrac{d\mathbf{x}}{dt} = \mathbf{A}\cdot\mathbf{x} + \mathbf{B}\cdot u \\ y = \mathbf{C}\cdot\mathbf{x} \end{cases} \qquad ..(1)$$

$\mathbf{A}\in\mathbf{R}^{n\times n}$, $\mathbf{B}\in\mathbf{R}^{n\times n}$, $\mathbf{C}\in\mathbf{R}^{n\times n}$,
$\mathrm{rank}\mathbf{B} = m$, $\mathbf{C} = \mathrm{col}(\mathbf{c}_1,\cdots,\mathbf{c}_m)$.

We define a decoupling matrix as:

$$\mathbf{D} \equiv \begin{bmatrix} \mathrm{c}_1 \mathbf{A}^{d_1 - 1}\mathbf{B} \\ \vdots \\ \mathrm{c}_m \mathbf{A}^{d_m - 1}\mathbf{B} \end{bmatrix} \quad ..(2)$$

which is nonsingular. Here, d_i $(1 \le i \le m)$, as defined below, is a relative order corresponding to each output:

$$d_i \equiv \min\{k \mid \mathbf{c}_i \mathbf{A}^{k-1}\mathbf{B} \ne 0\}. \quad ..(3)$$

A robust servo system is thus obtained based on the so-called internal model principle, as shown in Fig.1, with the internal model:

$$\begin{cases} \dot{\mathbf{x}}_c = \mathbf{A}_c \mathbf{x}_c + \mathbf{B}_c \mathbf{u}_c \\ \mathbf{A}_c \equiv \mathrm{blockdiag}\{\mathbf{A}_r, \cdots \mathbf{A}_r\} \in \mathbf{R}^{mq \times mq} \\ \mathbf{B}_c \equiv \mathrm{blockdiag}\{\mathbf{B}_r, \cdots \mathbf{B}_r\} \in \mathbf{R}^{mq \times mq} \\ \mathbf{B}_r \equiv [0, \cdots, 0, 1]^T \in \mathbf{R}^{q \times 1} \end{cases} \quad ..(4)$$

if the gain $\Sigma K_{F,0}$ and $\Sigma K_{C,0}$ in Fig.1 are chosen so as to stabilize the control system.

In this theory, the designer can specify asymptotically a desired transfer function $G_{yr}^{\infty}(s)$ from reference $\mathbf{r}$ to output $\mathbf{y}$, within a relative order in the decoupled form, as the tuning parameter $\mathbf{\Sigma} = \mathrm{diag}_{1 \le i \le m}\{\sigma_i\}\ (\sigma_i \ge 0)$ tends to infinity. The desired transfer function $G_{yr}^{\infty}(s)$ can realize the desired response of control.

Now, the desired transfer function is defined as $\mathbf{G}_{yr}^{\infty}(s) \equiv \lim_{\Sigma \to \infty} \mathbf{G}_{yr}(s)$ and is specified as a stable proper transfer function in the form:

$$\mathbf{G}_{yr}^{\infty}(s) = \mathrm{diag}_{1 \le i \le m}\left\{\frac{R_i(s)}{\phi_i(s)}\right\} \quad ..(5)$$

The denominator $\phi_i(s)$ and the numerator $R_i(s)$ are related by the following equation.

$$\phi_i(s) = \psi_i(s)\alpha(s) + R_i(s) \quad ..(6)$$

$$R_i(s) \equiv r_{i,q-1}s^{q-1} + \cdots + r_{i,1}s + r_{i,0} \quad ..(7)$$

$$\deg\{\phi_i(s)\} = d_i + q - 1 \quad ..(8)$$

$$\deg\{\psi_i(s)\} = d_i - 1 \quad ..(9)$$

$$\alpha(s) \equiv \det(s\mathbf{I} - \mathbf{A}_r) \quad ..(10)$$

where $\psi_i(s)$ is the quotient of the denominator $\phi_i(s)$ of the desired transfer function $G_{yr}^{\infty}(s)$ divided by the characteristic polynomial $\alpha(s)$ of $\mathbf{A}_r$ which is closely related to the internal model, whereas $R_i(s)$ is its remainder. Then the nominal feedback gains $K_{F,0}$ and $K_{C,0}$ are calculated in a closed form as:

$$\mathbf{K}_{F,0} = \mathbf{D}^{-1} \begin{bmatrix} \mathbf{c}_1 \psi_1(\mathbf{A}) \\ \vdots \\ \mathbf{c}_m \psi_m(\mathbf{A}) \end{bmatrix} \quad ..(11)$$

$$\mathbf{K}_{C,0} = \mathbf{D}^{-1}\, \mathrm{blockdiag}_{1 \le i \le m}\{[r_{i,0} \ \cdots \ r_{i,q-1}]\} \quad ..(12)$$

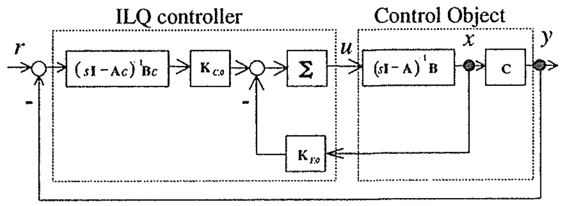

Fig.1 - Configuration of ILQ servo system

2. ILQ for rope type elevators

(1) Modeling

Figure 2 shows a typical rope-type elevator. The main control board inputs the cage speed reference and calculates motor speed reference. Then the main control board outputs the motor speed reference to the drive unit. The drive unit controls the motor speed according to the speed reference to manipulate the motor voltage and current. The motor drives the main sheave.

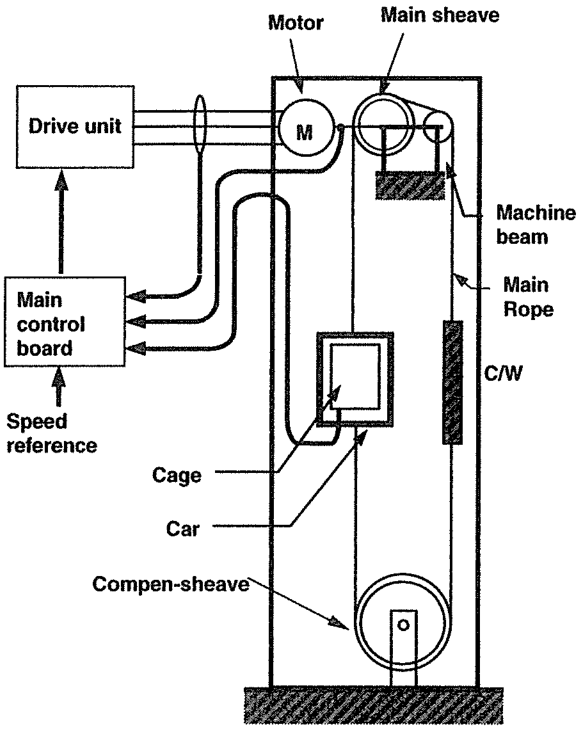

Figure 2 - Schematic diagram of rope elevator

A mathematical model for designing ILQ controller is shown by following equations,

$$\begin{cases} \frac{d\mathbf{x}}{dt} = \mathbf{A}\cdot\mathbf{x} + \mathbf{B}\cdot\omega_{m,ref} \\ v_{ca} = \mathbf{C}\cdot\mathbf{x} \end{cases} \quad ..(13)$$

$$\mathbf{x} = \begin{bmatrix} x_1 & \omega_m & \alpha_{cu} & v_{ca} & \alpha_{fu} & v_{cw} \end{bmatrix}^T ..(14)$$

where v_{ca} is the cage speed [m/s], v_{cw} is the counter weight speed [m/s], ω_m is the motor rotational speed [rad/s], α_{cu} and α_{fu} are the accelerations applied to cage and counter-weight, respectively, [m/s^2], and x_I is the integrator output of the motor speed controller [N/m].

The coefficient matrices **A**, **B**, and **C** are shown as follows,

$$\mathbf{A} = \begin{bmatrix} 0 & k_{PI} & 0 & 0 & 0 & 0 \\ \frac{1}{J} & -\frac{k_{PI}T_{PI}}{J} & -\frac{r_s M_{ca}}{J} & 0 & \frac{r_s M_{cw}}{J} & 0 \\ 0 & \frac{k_{ca} r_s}{M_{ca}} & 0 & -\frac{k_{ca}}{M_{ca}} & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & -\frac{k_{cw} r_s}{M_{cw}} & 0 & 0 & 0 & \frac{k_{cw}}{M_{cw}} \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} .(15)$$

$$\mathbf{B} = \begin{bmatrix} k_{PI} & \frac{k_{PI}T_{PI}}{J} & 0 & 0 & 0 & 0 \end{bmatrix}^T \quad ..(16)$$

$$\mathbf{C} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \quad ..(17)$$

where J is the motor and the main sheave inertia [$kg.m$], r_s is the main sheave radius [m], M_{ca} is the total weight of car and passengers, M_{cw} is the weight of the counter weight, k_{ca} and k_{cw} are the spring coefficient of the upper side main rope of the car and the counter weight, respectively, and k_{PI} and T_{PI} are the gain and the time constant of the drive unit, respectively.

(2) ILQ controller design

Given the desired response of cage speed control ω_{da} rad/s, the cage speed controller is designed according to the ILQ theory.

The decoupling constant D is expressed by the following equations whose relative order d is three.

$$D = \mathbf{CA}^2\mathbf{B} = \frac{k_{PI}T_{PI}k_{ca}r_s}{JM_{ca}} (\neq 0) \quad ..(18)$$

The desired transfer function G_{yr}^{∞}, that is the closed loop transfer function of cage speed control, is set as follows:

$$G_{yr}^{\infty}(s) = \omega_{da}^3 / (\omega_{da} + s)^3 \quad ..(19)$$

where $\alpha(s)$ is chosen "s" meaning an integral controller. The feedback gain K_{F0} and the main controller gain K_{c0} are calculated as follows,

$$K_{F0} = \frac{J}{k_{PI}T_{PI}} \cdot \begin{bmatrix} 0 & 1 & k_{f3} & k_{f4} & 0 & 0 \end{bmatrix} \quad ..(20)$$

$$K_{c0} = \frac{JM_{ca}\omega_{da}^3}{k_{PI}T_{PI}k_{ca}r_s} \quad ..(21)$$

$$k_{f3} = (3M_{ca}\omega_{da})/(k_{ca}r_s) \quad ..(22)$$

$$k_{f4} = (3M_{ca}\omega_{da}^2)/(k_{ca}r_s) - 1/r_s\,. \quad ..(23)$$

The speed reference of the motor is expressed by the following equation

$$\omega_{m,ref} = \sigma \cdot \left\{ \frac{k_{c0}}{s}(r-y) - k_{F0}\mathbf{x} \right\}, \quad ..(24)$$

where σ is the tuning parameter to obtain the desired stable speed control response.

The rope spring coefficient k_{ca} varies the car position. This relationship is expressed by following equation:

$$k_{ca} = k_{ca,o}/l\,, \quad ..(25)$$

where $k_{ca,0}$ is the main rope spring coefficient of unit length and l is the rope length between the main sheave and the car. Figure 3 is a block diagram of the cage speed control system for rope type elevators.

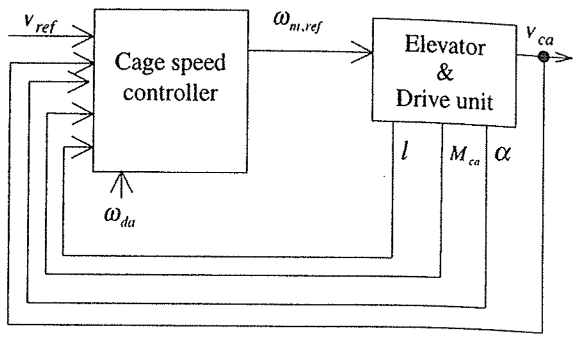

Fig.3 - Schematic diagram of cage speed control applying ILQ theory

(3) Evaluation of ILQ control

Figures 4 and 5 show the effect of cage speed control applying ILQ theory. Simulation is performed under the following conditions:

. Height: 600m,

. Maximum speed: 1000mpm, and

. Disturbance: motor torque ripple.

Figure 4 shows the results of conventional control without cage speed control and fig. 5 shows the results of the new control with the cage speed controller. In figure 4, cage acceleration fluctuates due to rope resonance frequency and motor torque ripple. Vibration frequency varies according to the car position and speed. It could not achieve sufficient passengers' riding comfort. It is necessary to select low acceleration/ deceleration rate in order to reduce vibration caused by the rope spring, but it affects flight time.

Figure 5 shows small fluctuations of cage and car acceleration. It indicates that the cage speed controller applying ILQ theory maintains good riding comfort.

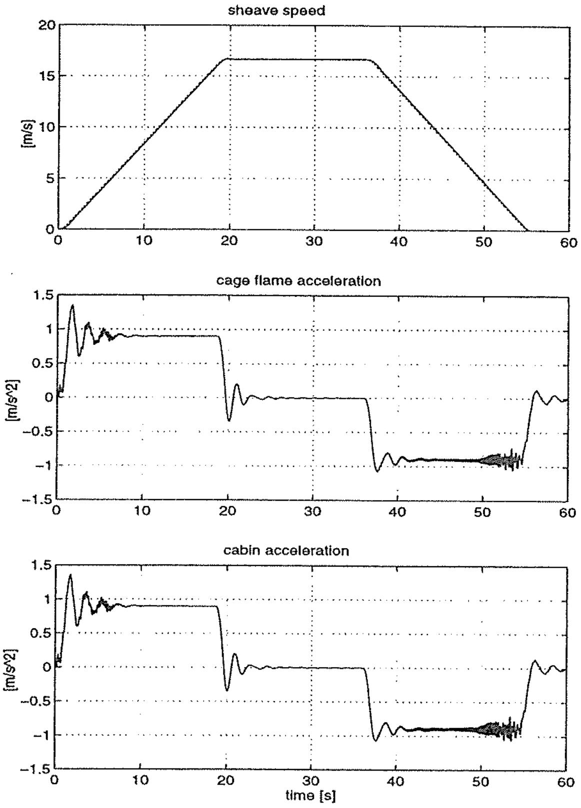

Fig.4 - Simulation results of conventional control without cage speed control

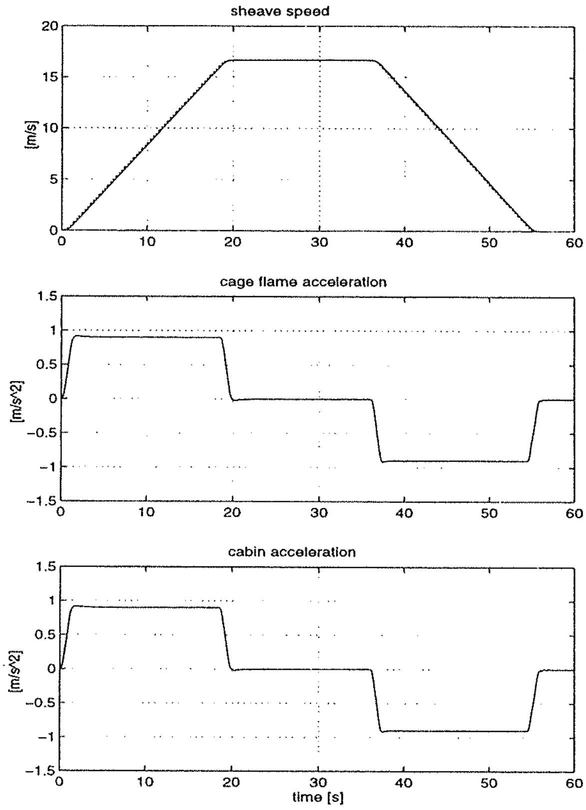

Fig.5 – Simulation results of new speed control with cage speed controller

3. ILQ for hydraulic elevators

(1) Modeling

Figure 6 shows a schematic diagram of a hydraulic elevator. The inverter manipulates the motor speed in order to push up the plunger and down. The cage goes up and down according to the plunger position. There is a problem that oil compression causes another resonance frequency, making difficult to obtain stable cage speed control.

The hydraulic pump generally has oil leakage and the oil leakage depends mainly on oil temperature and pressure.

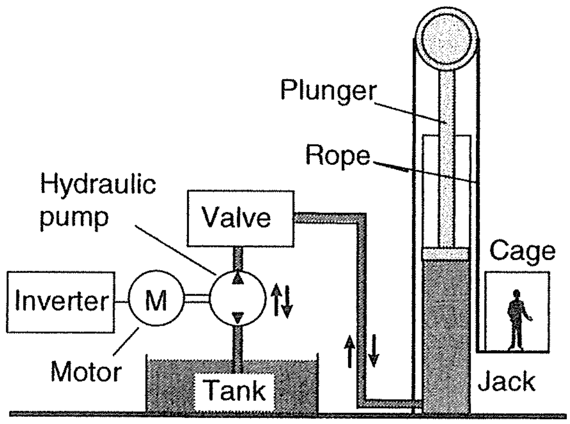

Fig.6 - Schematic diagram of hydraulic elevator

Figure 7 shows a sample of these relationships. The cage speed differs due to oil temperature and pressure that reflects cage load.

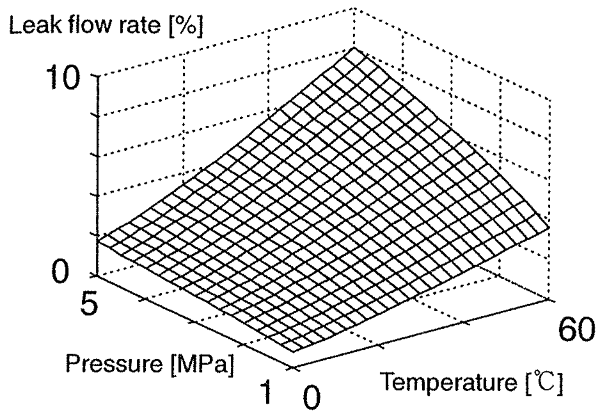

Fig.7 - Leak flow rate of hydraulic pump

The mathematical model is expressed as follows,

$$\begin{cases} \dfrac{d\mathbf{x}}{dt} = \mathbf{A}\cdot\mathbf{x} + \mathbf{B}\cdot\omega_{m,r} \\ v_{ca} = \mathbf{C}\cdot\mathbf{x} \end{cases} \quad ..(26)$$

$$\mathbf{x} = [x_{PI} \quad \omega_p \quad P_j \quad v_p \quad \alpha_{ca} \quad v_{ca}]^T \quad ..(27)$$

$$A = \begin{bmatrix} 0 & -\frac{1}{T_1} & 0 & 0 & 0 & 0 \\ \frac{1}{J_p} & -\frac{T_2}{T_1 J_p} & -\frac{q}{J_p} & 0 & 0 & 0 \\ 0 & \frac{q}{\beta\cdot V_j} & 0 & -\frac{A_j}{\beta\cdot V_j} & 0 & 0 \\ 0 & 0 & \frac{A_j}{M_j} & 0 & -\frac{2\cdot M_c}{M_j} & 0 \\ 0 & 0 & 0 & \frac{2\cdot K}{M_c} & 0 & -\frac{K}{M_c} \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \quad ..(28)$$

$$B = \begin{bmatrix} \frac{K_1}{T_1} & \frac{T_2\cdot K_1}{T_1 J_p} & 0 & 0 & 0 & 0 \end{bmatrix}^T \quad ..(29)$$

$$C = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1] \quad ..(30)$$

and

$$K_1 = A_j/2/q. \quad ..(31)$$

The symbols are listed as follows:

$\omega_{m,r}$ is motor speed reference [*rad/s*], v_{ca} is cage speed [m/s], ω_p is pump rotational speed [*rad/s*], P_j is jack pressure [*Pa*], v_p is plunger speed [*m/s*], α_{ca} is acceleration applied to the cage [m/s^2], M_j is plunger weight [*kg*], M_c is car weight including passenger weight [*kg*], K is rope spring coefficient [*N/m*], A_j is the internal cross sectional area of the jack [m^2], J_p is the inertia of the pump and the motor [$kg.m^2$], q is pump outlet flow [m^3/rad], β is oil compression factor [1/*Pa*], V_j is oil volume in the jack [m^3], T_1, T_2 are time constants of the motor speed controller, and x_{PI} is the integrator output value of the motor speed controller.

(2) ILQ controller design

For designing the ILQ controller, the order of the mathematical model is reduced using singular perturbation methods in order to simplify the structure of the cage speed controller. The jack pressure and the cage speed are selected as the state variables. The state variables can be separated into the following two groups;

$$x_1 = [P_j \quad v_{ca}]^T \quad ..(32)$$

and

$$x_2 = [x_{PI} \quad \omega_p \quad v_p \quad \alpha_{ca}]^T. \quad ..(33)$$

Then the model is reduced as follows:

$$\begin{cases} \dot{x}_1 = A_d\cdot x_1 + B_d\cdot\omega_{m,ref} \\ v_{ca} = C_d\cdot x_1 \end{cases} \quad ..(34)$$

$$A_d = \begin{bmatrix} 0 & -A_j/(2\beta V_j) \\ -A_j/(2M_c) & 0 \end{bmatrix} \quad ..(35)$$

$$B_d = [(qK_1)/(\beta V_j) \quad 0]^T \quad ..(36)$$

$$C_d = [0 \quad 1]. \quad ..(37)$$

Given the desired response of cage speed control ω_{dh} *rad/s*, the cage speed controller is designed according to the ILQ theory. As the relative order of the reduced model is two, the desired transfer function G_{yr}^{∞} is set as follows:

$$G_{yr}^{\infty}(s) = \omega_{dh}^2 / (\omega_{dh} + s)^2 . \quad ..(38)$$

A similar calculation procedure to that of the rope type elevator is applied to the control law calculation for the hydraulic elevator. The feedback gain K_{F0} and the main controller gain K_{c0} are calculated as follows:

$$K_{F0} = \begin{bmatrix} \dfrac{2\beta V_j}{A_j} & \dfrac{8\beta V_j M_c \omega_{dh}}{A_j^2} \end{bmatrix} \quad ..(39)$$

$$K_{c0} = \frac{4\beta V_j M_c \omega_{dh}^2}{A_j^2} \quad ..(40)$$

The motor speed reference is then expressed as follows:

$$\omega_{m,r} = \sigma \cdot \left\{ \frac{k_{c0}}{s}(r - y) - k_{F0}\mathbf{x} \right\} . \quad ..(41)$$

(3) Evaluation of ILQ control

Figure 8 shows the pole assignment of the closed loop of the cage speed control. The calculation was performed using the 6th order model as the process and the 2nd order reduced model as the controller design. Figure 8 indicates that vibrations caused by oil compression and rope spring can be suppressed because the damping factor becomes large. Though ILQ theory guarantees a closed loop stable condition if the tuning parameter is selected over some value that ILQ theory has proved, there is an upper limit of the tuning parameter because the 2nd order reduced model is used to design the cage speed controller.

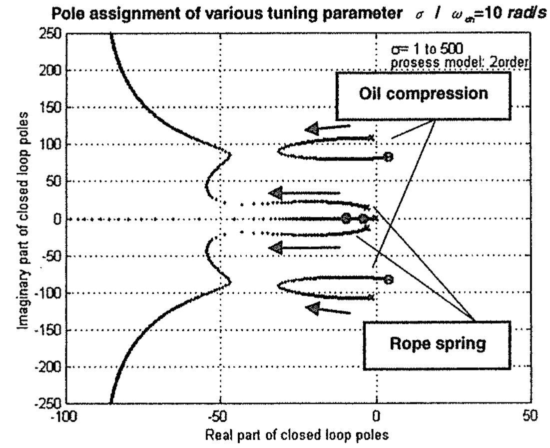

Fig.8 – Pole assignment of closed loop of cage speed control

Figures 9 - 12 show the experimental evaluation results of the cage speed control.

Figure 9 shows the conventional control without the cage speed controller under the conditions of no load and normal temperature. Figure 10 shows the conventional control without the cage speed controller under the conditions of full load and high temperature. The conventional control has only a speed bias function to remove the cage speed offset. These two figures show that the cage vibration is large, and the speed offset occurs at top speed.

Figure 11 shows the new control with the cage speed controller under the conditions of no load and normal temperature. Figure 12 shows the new control with the cage speed controller under the conditions of full load and high temperature. Figures 11 and 12 indicate that the cage acceleration is small, and the speed offset at top speed is almost nothing.

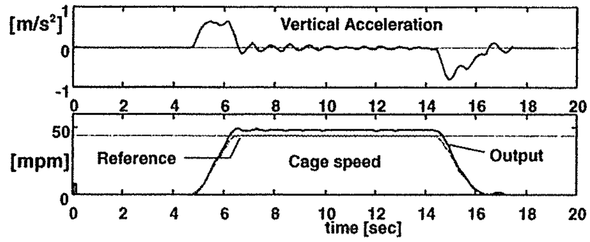

Fig.9 – Conventional control results: no Load, oil temp. 25C, without cage speed control

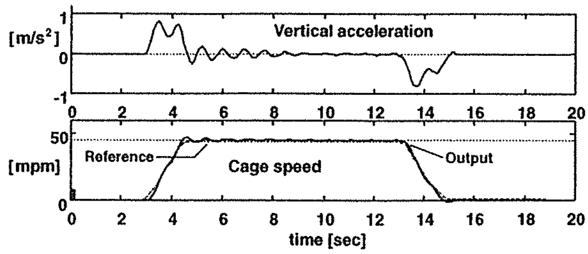

Fig.10 – Conventional control results: full load, oil temp. 50C, without cage speed control

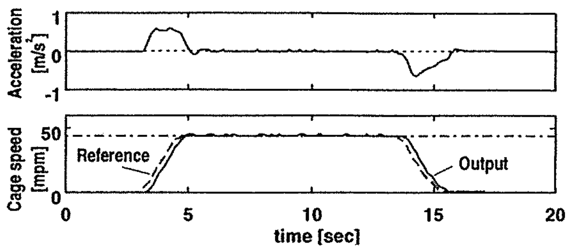

Fig.11 – New control results: no load, oil temp. 25C, with cage speed control

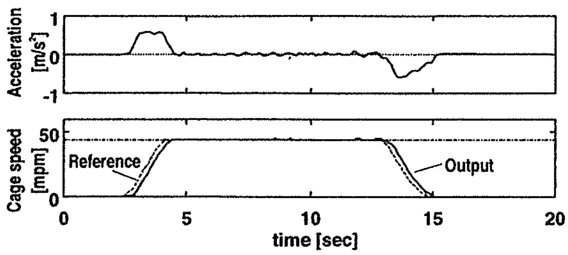

Fig.12 – New control results: full load, oil temp. 50C, with cage speed control

Figure 13 shows the cage vibration component analysis. Figure 13 indicates that a low frequency vibration of around 1 *Hz* caused by the rope spring is drastically reduced by the new control and that a high frequency vibration around 16 *Hz* caused by the oil compression has not been excited by the new control.

It is thus confirmed that the new control system reduces vertical vibrations achieving good riding comfort.

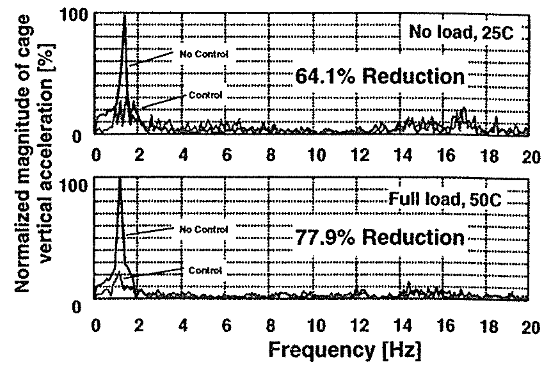

Fig.13 – Frequency component of vertical acceleration in the cage

4. Conclusions

New elevator speed control methods for rope type and hydraulic elevators are proposed, respectively. The control systems are derived by applying the ILQ theory. Computer simulations for the high-rise rope elevator and experimental results for the hydraulic elevator confirm that both of the new control systems show good vibration damping performance.

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Authors Biography

Yoshiro Seki graduated in Metallurgical Engineering from Kurume National College of Technology, Fukuoka, Japan, in 1974. After that, he joined Toshiba Corporation, Japan, where he has been engaged Industrial Systems Control Development Group of Power and Industrial systems Research and Development Center. Since 1998, he has been a Senior Specialist of control systems R&D engineers. He has developed many control systems for elevators, for steel rolling mills, and for vehicle engine test equipment, since 1974. His current interests are robust control theory, LMI theory, and their industrial applications.

Yasuhiro Hirashiki received B.E. and M.E. degrees all in Electrical Engineering from Yokohama National University, Yokohama, Japan, in 1980, 1982, respectively. He joined Toshiba Corporation, Japan, in 1982, where he has been engaged the Elevator Development Group of Elevator and Escalator Division. Since 1997, he has been a Senior Specialist of elevator electrical engineers.

Takao Fujii received the Bachelor, Master, and Doctor of Engineering degrees from Osaka University in 1967, 1969, and 1983, respectively. Since 1969 to 1989, he was with Osaka University as an Assistant and then Associate professor. In 1990 he joined the Department of Control System Engineering of Kyushu Institute of Technology as a Professor. In 1995 he moved to Osaka University, where he is currently a Professor of Control Engineering at the Department of Systems Science. His current research interests include linear quadratic control, robust control including H-infinity control as well as its application to magnetic levitation and industrial problems.