Proceedings of the 14th
KACC, Octorber 1999

An Identification of the Hydraulic Motion Simulator Using Modified Signal Compression Method and Its Application

°Min Kyu Park*, Min Cheol Lee**, Seok Jo Go*

* Graduate School of Intelligent Mechanical Engineering, Pusan National University, Pusan 609-735, Korea
(Tel : 82-51-510-3081; Fax : 82-51-512-9835; E-mail : mkpark@hyowon.pusan.ac.kr)
** School of Mechanical Engineering, Pusan National University, Pusan 609-735, Korea
(Tel : 82-51-510-2439; Fax : 82-51-512-9835; E-mail : mclee@hyowon.pusan.ac.kr)

Abstract

Many researches on the identification of a system have been carried out using a least square method, an adaptive filter, and so on. However, it is difficult to apply these methods in a nonlinear system. In the case of a nonlinear system, it is known that the signal compression method is able to estimate uncertain parameters of linear element in a nonlinear system because it is able to separate linear element and nonlinear element in a nonlinear system. However, the signal compression method cannot be applied to a motion simulator because actuators of the simulator is single-rod cylinders which includes expansion and compression dynamic properties. Therefore, this paper proposes a modified signal compression method which is able to estimate uncertain parameters of the motion simulator dynamics. The dynamic properties of this system are identified by separating expansion and compression properties when applying the signal compression method. And then, the identified parameters are applied to design a sliding mode controller for the simulator. The performance of the designed sliding mode controller is evaluated experimentally.

1. Introduction

A single-rod cylinder is widely used in a motion simulator which is called the Stewart platform, because it is longer in stroke and smaller in size than a double-rod cylinder. However, it is difficult to analyze dynamic properties because of non-linearity caused by a difference of each chamber volume. Many other researches on the identification of linear system have been carried out using a least square method, an adaptive filter, and so on. However, it is hard to apply these methods in a nonlinear system, because these algorithms are developed on a linear system[1]. In the case of a nonlinear system, the signal compression method estimates uncertain parameters of linear element in a nonlinear system because it is able to separate linear element and nonlinear element in a nonlinear system[1,2]. However, the signal compression method cannot be applied to the motion simulator including hydraulic actuators because the actuators have different dynamic properties according to its motion.

This paper proposes a modified signal compression method which estimates uncertain parameters of the hydraulic motion simulator including single-rod cylinders with two dynamics. The dynamic properties of this system are identified by separating expansion and compression properties when applying the signal compression method. To evaluate the performance of the proposed method, the response of the identified model by simulation is compared with that of the real system by experiment. And then, a sliding mode controller[3] is designed on the base of the identified model of the motion simulator. And the performance of the designed sliding mode controller is evaluated experimentally.

2. Modified Signal Compression Method

2.1 Signal Compression Method

An ideal impulse is desired to obtain the flat power spectrum in a wide frequency range. However, it is sufficient in a practical measurement for an impulse to have a flat power spectrum in a limited frequency range[1]. The waveform having a property of impulse can be Fourier transformed and passed through a mathematical phase-shift filter. Then, the signal has a constant power and phase delay. If this signal in the frequency domain is transformed into the time domain through the inverse Fourier transformation, the test signal might have a low amplitude

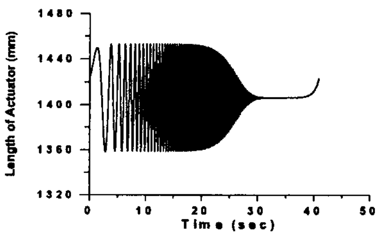


Fig. 1 Test signal

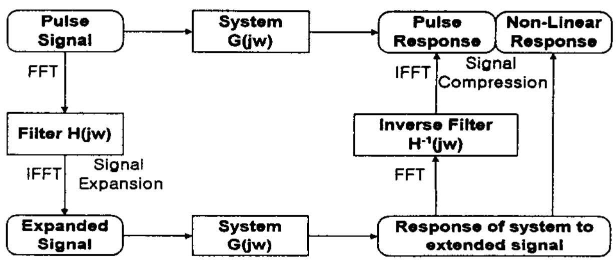


Fig. 2 Block diagram of signal compression method

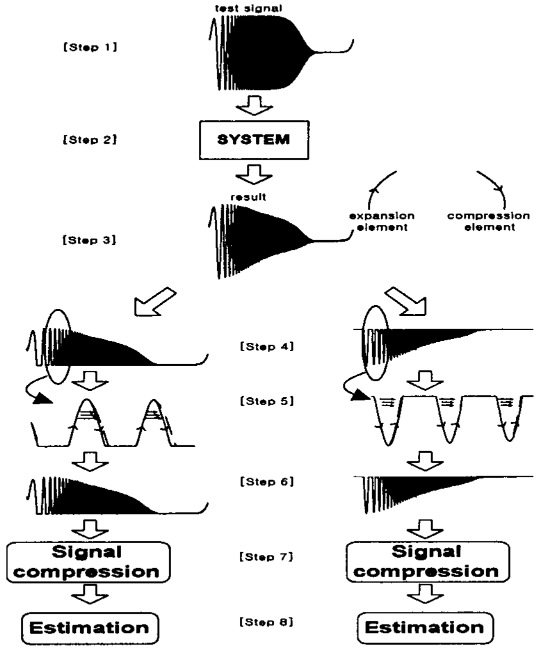


Fig. 3 Separation method of dynamic properties

and lasted for a long time, as shown in Fig. 1[1,2]. The test signal is applied to a system, in order to estimate uncertain parameters. A response obtained by supplying the system can be compressed through fast Fourier transform(FFT), inverse phase-shift filter, and inverse FFT. In this compression process, impulse response for linear element can be indirectly obtained, because of being able to separate of linear and nonlinear element in the system. These processes as a whole are known as a signal compression method(SCM). Fig. 2 is a general schematic diagram of the signal compression method[2].

2.2 Modified Signal Compression Method

A single-rod cylinder, the actuator of a motion simulator, is a representative system which includes two different dynamic properties according to its motion. This paper proposes a modified signal compression method which is able to estimate uncertain parameters of the motion simulator including single-rod cylinders. The dynamic properties of this system are identified by separating expansion and compression properties when applying the signal compression method, as shown in Fig. 3. The procedures of Fig. 3 are as follows:

[Step1] Generate the test signal of SCM.
[Step2] Apply test signal to a measuring system.
[Step3] Obtain and normalize output signal of the system.
[Step4] Separate upper part and lower part signal of normalized output signal.
[Step5] Remove compression element in upper part and then recover the removed part using expansion element. In lower part, apply same method.
[Step6] Apply this method in whole range. Therefore, expansion element exists in upper part and compression element exists in lower part.
[Step7] Obtain pulse response by signal compression respectively.
[Step8] Estimate uncertain parameters by comparing Bode plot from the transfer function of a model and that from the obtained pulse response.

The system which includes two different dynamic properties according to its motion is identified by this procedures. And this method was verified by various simulation[4].

3. Identification of Motion Simulator

3.1 Modeling of Stewart Platform

The dynamic equation of the Stewart platform considering all inertia effect is known to be very difficult to derive, if not impossible. Lebret derived the dynamic equation using the Euler-Lagrange method and virtual work principle[5]. This equation can be written as (1).

$$M_P(q)\,\ddot{q}+C_P(q,\dot{q})\dot{q}+G_P(q)=J^T U_P \tag{1}$$

$q=[x,y,z,\alpha,\beta,\gamma]$ is coordinates vector of the upper centroid; α,β,γ are the rotational angles about the x,y,z axes. $M_P(q)\in R^{6\times 6}$ is the inertia matrix, $C_P(q)\in R^{6\times 6}$ corresponds to the centrifugal and Coriolis forces matirx, $G_P(q)\in R^{6\times 1}$ is the gravity force vector, $J(q)\in R^{6\times 6}$ is jacobian matirx, and $U_P(q)\in R^{6\times 1}$ is cylinder force vector. After some algebraic operation($\dot{l}=J\dot{q}$) and kinematic transformation, equation (1) can be expressed as (2)

$$\widetilde{M_P}(q)\,\ddot{l}+\widetilde{C_P}(q,\dot{q})\,\dot{l}+\widetilde{G_P}(q)=U_P \tag{2}$$

Where, $l=[l_1,l_2,l_3,l_4,l_5,l_6]$ is cylinder length vector.

$$\widetilde{M_P}(q)=J^{-T}(q)M(q)J^{-1}(q)$$

$$\widetilde{C_P}(q,\dot{q})=J^{-T}(q)M(q)\frac{d}{dt}J^{-1}(q)+J^{-T}(q)C(q,\dot{q})J^{-1}(q)$$

$$\widetilde{G_P}(q)=J^{-T}(q)G(q)$$

In the case of cylinder dynamic equation, it is high order nonlinear equation. Assuming that such a complex nonlinear part acts as a disturbance to the model, simple linear dynamics is obtained such as (3).

$$M_A\ddot{l}+C_A\dot{l}+U_P=K_{SV}U_A \tag{3}$$

M_A is the summation of equivalent masses of all the translational part in the cylinder. C_A is the equivalent damping coefficient. K_{SV} is a spool constant. Therefore, the complete nominal dynamic equation of the Stewart platform system including the manipulator and cylinder dynamics becomes (4).

$$M_T(q)\,\ddot{l}+C_T(q,\dot{q})\,\dot{l}+G_T(q)=K_{SV}U_A \tag{4}$$

Where, $M_T=\widetilde{M_P}+M_A$, $C_T=\widetilde{C_P}+C_A$, $G_T=\widetilde{G_P}(q)$

After separating linear element and nonlinear element in equation (4), this equation can be re-expressed as (5).

$$M_{TL}\ddot{l}+C_{TL}\dot{l}+F=K_{SV}U_A \tag{5}$$

M_{TL} and C_{TL} is the summation of all linear terms in M_T and C_T. The disturbance term F is the summation of the nonlinear terms of inertia moments, the Coriolis and centrifugal force, the gravity force and the friction term.

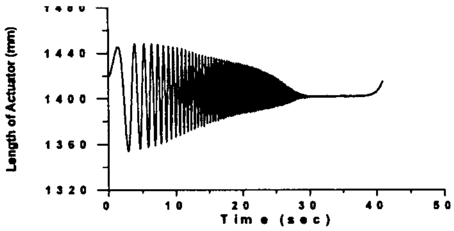
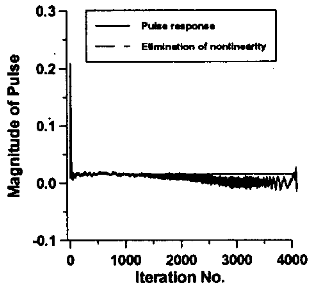


Fig. 4 Response from the single rod cylinder by the test signal



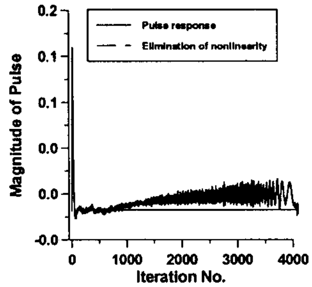
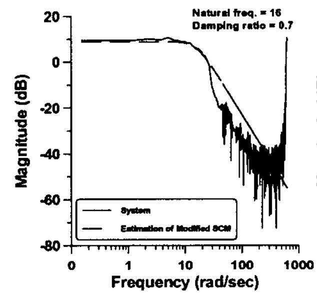


Fig. 5 Impulse response of expansion

Fig. 6 Impulse response of compression



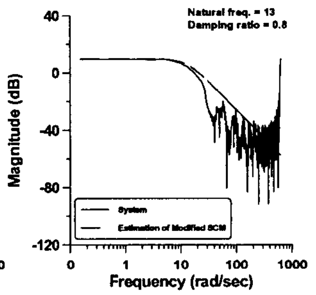


Fig. 7 Bode plot of expansion

Fig. 8 Bode plot of compression

3.2 Estimation of Uncertain Parameters

The test signal in Fig. 1 is used to estimate uncertain parameters of the motion simulator. The test signal is supplied through the D/A converter. The length of the cylinder moving according to the supplied test signal is detected by linear differential transduser and A/D converter. The output signal is shown in Fig. 4. It is known that the dynamic properties in expansion and compression motion are different each other. Therefore, separating expansion and compression motion is carried out. And the separated signals are changed into those in the frequency domain by the FFT program written in C language and passed through the mathematical inverse phase-shift filter, and then, the element contributed by the nonlinear component is removed to obtain the pulse response like Fig. 5 and Fig. 6. Fig. 5 is the pulse response from expansion motion, Fig. 6 is that from compression motion.

As comparing Bode plot of the transfer function from a model and that from obtained pulse response, natural frequency(ω_n) and damping coeffiecient(ζ) are estimated as shown in Fig. 7 and Fig. 8. As these processes are applied to all cylinders of the motion simulator, the natural frequency and damping coeffiecient of each actuator are obtained. Therefore, uncertain parameters of equation (5) are obtained by the natural frequency and damping coeffiencient. Table 1 shows the estiamted equivalent mass and damping coefficient of each cylinder.

Fig. 9 shows the output result from the identified model when the test signal is supplied to the model. It is verified that the proposed method is valid because the output signal from identified model is similar to that from real system.

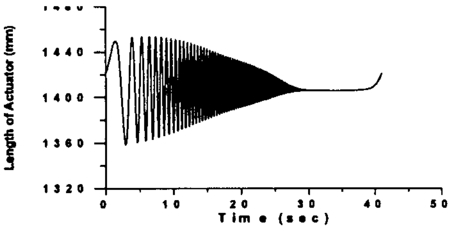
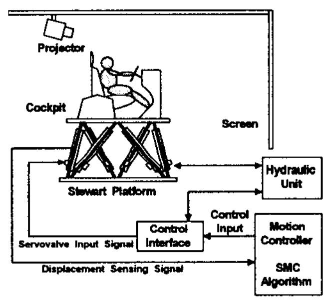


Fig. 9 Response from the identified model by the test signal

Table 1 Estimation result for Stewart plaform

Cylinder No.	Direction	ω_n, ζ	$M_{TL}(kg)$, C_{TL}
cylinder 1	expansion	16.0 , 0.7	90.8 , 2034.1
	compression	13.0 , 0.8	91.7 , 2024.8
cylinder 2	expansion	15.0 , 0.7	103.3 , 2169.7
	compression	13.0 , 0.8	91.7 , 2024.4
cylinder 3	expansion	15.0 , 0.7	103.3 , 2169.7
	compression	14.0 , 0.7	79.1 , 1771.3
cylinder 4	expansion	15.0 , 0.7	103.3 , 2169.7
	compression	14.5 , 0.8	73.7 , 2024.4
cylinder 5	expansion	15.5 , 0.7	96.8 , 2099.7
	compression	14.5 , 0.8	85.0 , 1959.1
cylinder 6	expansion	15.0 , 0.7	103.3 , 2169.7
	compression	13.0 , 0.8	91.7 , 2024.8



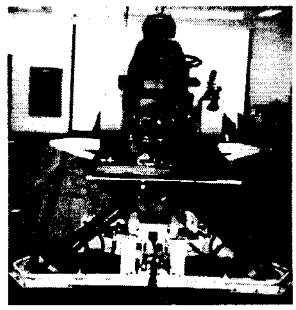


Fig. 10 Block diagram of control system

Fig. 11 Stewart platform and cockpit

4. Application to Sliding Mode Control

4.1 Design of Sliding Mode Controller in Joint-Axis

In this study, the control system is developed to control a position of the Stewart platform in real-time[6]. The schematic diagram of the control system is shown in Fig. 10. The micro-processor of the control board is 80C196KC. For improving computational ability, one micro-processor controls two cylinders. Therefore, the motion controller is composed of three control boards. Fig. 11 shows the developed motion simulator and cockpit system[6].

The dynamic system in the presence of disturbance and perturbation can be represented as equation (5). The parameters of this equation were estimated by the modified signal compression method. The sliding surface(s) is defined by equation (6).

$$s_j = \dot{e}_j + c_j e_j \quad j = 1, 2, \cdots, 6 \quad (6)$$

where $e_j = l_j - l_{d,j}$, the positive constant c_j is the desired control bandwidth, l_j and $l_{d,j}$ are the measured and desired cylinder lengths, respectively. Let the time derivative of the Lyapunov function candidate be given by $s\dot{s} < 0$ to satisfy the boundary layer attraction condition. When the unmodeled nonlinear terms are replaced by disturbances, a control input is proposed as follows[3]:

$$U_A = u_i = \psi_{\alpha i} e_i + sat(\psi_{fi}) + \psi_{\beta i} \dot{l}_{di} + \psi_{\gamma i} \dot{l}_{di} \quad (7)$$

$$\begin{cases} K_{SV,i}\psi_{\alpha,i} + C_{TL,i}c_i - M_{TL,i}c_i^2 < 0 & \text{if} \quad s_i e_i > 0 \\ -K_{SV,i}\psi_{\alpha,i} + C_{TL,i}c_i - M_{TL,i}c_i^2 > 0 & \text{if} \quad s_i e_i < 0 \end{cases}$$

$$\begin{cases} \psi_{f,i} = M_{1,i} + M_{2,i}|e_i| < F_i / K_{SV,i} & \text{if} \quad s_i > 0 \\ \psi_{f,i} = -M_{1,i} - M_{2,i}|e_i| > F_i / K_{SV,i} & \text{if} \quad s_i < 0 \end{cases}$$

$$\begin{cases} K_{SV,i}\psi_{\beta,i} - C_{TL,i} < 0 & \text{if} \quad s_i \dot{l}_{di} > 0 \\ -K_{SV,i}\psi_{\beta,i} - C_{TL,i} > 0 & \text{if} \quad s_i \dot{l}_{di} < 0 \end{cases}$$

$$\begin{cases} K_{SV,i}\psi_{\gamma,i} - M_{TL,i} < 0 & \text{if} \quad s_i \ddot{l}_{di} > 0 \\ -K_{SV,i}\psi_{\gamma,i} - M_{TL,i} > 0 & \text{if} \quad s_i \ddot{l}_{di} < 0 \end{cases}$$

where $\psi_{\beta i}$ and $\psi_{\gamma i}$ are feedforward control input terms to satisfy the existence condition of sliding mode against unfavorable effects of $\dot{l}_{di}$ and $\dot{l}_{di}$ on the trajectory tracking. $sat(\psi_{fi})$ is the modified control input for compensating disturbances[3].

4.2 Experimentation

A simple tracking control is performed to check the identified model. The tuned control parameters are c_j = 20, $\psi_{\alpha,j}$ = -8 ~ -10, $\psi_{\beta,j}$ = -1 ~ -3, $\psi_{\gamma,j}$ = -1 ~ -2, $M_{1,j}$ = -10 ~ -0.1, $M_{2,j}$ = -2. The payload of the system is about 250kg. The sampling time interval for control is selected by 10msec because response frequency of servovalve is 100Hz.

The reference trajectories and tracking trajectories are shown in Fig. 12. Fig. 13 shows tracking position errors. Fig. 14 is reference velocity trajectory and tracking velocity for cylinder 2. In fast motion for z-axis, maximum error is about 4mm. However, average error for the whole of motion is within 2.5mm. Therefore, the tracking performance of designed SMC is relatively good.

5. Conclusion

It is difficult to analyze the dynamic properties of a system including single-rod cylinders by general identification method, because of non-linearity caused by difference of each chamber volume.

This paper proposed a new identification method which is able to estimates uncertain parameters of this system dynamics using separation of dynamic properties and signal compression method. And, as its application, a sliding mode controller was designed on the base of the identified model for the Stewart platform, and evaluated experimentally. The tracking performance of the designed SMC was relatively good. Therefore, it is proved that the identified model for the Stewart platform by the proposed method is valid.

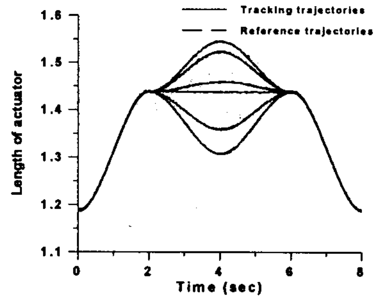


Fig. 12 Reference trajectories and tracking trajectories

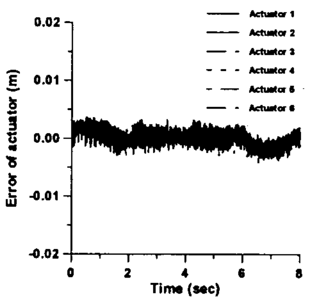


Fig. 13 Tracking errors

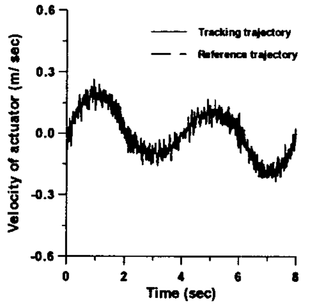


Fig. 14 Velocity trajectory

Acknowledgment

This research was supported by the KOSEF(Korea Science and Engineering Foundation, basic research grants : 97-02-00-10-01-5)

References

[1] M. C. Lee and N. Aoshima, "Identification and Its evaluation of the System with a Nonlinear Element by Signal Compression Method," Trans. of SICE, Vol.25, No.7, pp. 729-736, 1989. (in Japanese)

[2] S. Y. Jin, M. C. Lee, K. Son, "Study on the Identification of Dynamic System with Nonlinear Terms Using Signal Compression Method and Correlation Coeffiecient," *93' Proceeding of KSME Spring Aunual*, pp. 519-523, 1993. (in Korean)

[3] M. C. Lee, K. Son, J. M. Lee, "Improving Tracking Performance of Industrial SCARA Robots Using a New Sliding Mode Control Algorithm," KSME International Journal, Vol. 12, No. 5 pp. 761-772, 1998.

[4] M. K. Park, M. C. Lee, S. J. Go, M. C. Han, " The Identification of Dynamics of Actuator for Hydraulic Simulator System Using Modified Signal Compression Method," *99 proceeding of KSPE Spring Aunual*, pp. 162-165, 1999. (in Korean)

[5] Lebret, G. Liu, K., and Lewis, F.L., " Dynamic Analysis and Control of a Stewart Platform Manipulator," Journal of Robotic Systems, Vol. 10, No. 5, pp. 629-655, 1993

[6] M.K. Park, M. C. Lee, K. Son, W. S. Yoo, M.C. Han, J. M. Lee, "A Study on the Development of Driving Simulator for Reappearance of Vehicle Motion(I)," Journal of KSPE, Vol. 16, No. 6, pp. 90-99, 1999. (in Korean)