AN ELECTRO-HYDRAULIC SERVO MECHANISM WITH AN ANALOG ADAPTIVE CONTROLLER

Kazushi Sanada, Yoshiyasu Hagiwara, Ato Kitagawa

Dept. of Control Engineering
Faculty of Engineering
Tokyo Institute of Technology
Tokyo, Japan

ABSTRACT

In recent years, many studies on the adaptive control of an oilhydraulic servomechanism using a microcomputer have been done. A microcomputer has merits of flexibility of algorithm and high computing accuracy. But the computing time of the discrete adaptive law is not short enough to control an oilhydraulic servomechanism in high frequency region. For control of an oilhydraulic servomechanism in higher frequency region, there are two methods. One is a method of using a digital signal processor, and the other is a method of using an analog adaptive controller. The analog adaptive controller has a merit that its computing time is theoretically zero. In this study, the adaptive law was constructed in continuous time description and the adaptive controller was realized by an analog electronic circuit which was designed using a CAD program. And experiments were conducted to investigate the electrohydraulic servomechanism with the analog adaptive controller.

KEYWORDS

Electrohydraulic Servomechanism,
Adaptive Control, CAD,
Analog Adaptive Controller

NOMENCLATURE

a : linearized parameter
 a_M : reference model parameter
 b : linearized parameter
 b_M : reference model parameter

E : Laplace transform of e
 E_v : Laplace transform of e_v
 e : position error signal
 e_v : velocity error signal
 F_L : Liapunov function
 K_v : velocity transducer gain
 K_V : potentiometer gain
 K_1, K_2 : gains
 K_{10}, K_{20} : initial values of gains
 K_1, K_2
 R : Laplace transform of r
 r : position demand signal
 s : Laplace variable
 t : time
 U : Laplace transform of u
 u : signal fed to a servo amplifier
 V : Laplace transform of v
 V_M : Laplace transform of v_M
 v : load velocity
 v_M : reference model velocity signal
 Y : Laplace transform of y
 y : load position
 γ_1, γ_2 : adaptive gain
 I^* : adaptive gain matrix
 ζ : damping ratio
 ζ : column vector
 θ : column vector
 ω_n : natural angular frequency

Superscript

T : transposed matrix
 $^{-1}$: inverse matrix

INTRODUCTION

In recent years, many studies on the adaptive control of an oilhydraulic servomechanism have been done (1)~(4). In these studies, microcomputers were used as adaptive controllers. A microcomputer has

merits of control algorithm flexibility and high computing accuracy. For realizing an adaptive control system with a microcomputer, the adaptive control law must be constructed in discrete time description. Since the discrete-time adaptive control law contains many computations of the four rules of arithmetic, the calculation of one cycle of the control law using a microcomputer needs at least several milliseconds. For this computing time, sampling interval may not be designed short enough to control an oilhydraulic servomechanism in high frequency region and to realize a high-speed servo system.

There are two methods in order to realize a high speed adaptive system. One is a method of using a digital signal processor. By this method, computing time can be considerably shortened. The other is a method of using an analog adaptive controller. In the latter method, the adaptive control law is constructed in continuous time description and an adaptive controller is realized by an analog electronic circuit (5). In order to make the adaptive control more practical control method for an electrohydraulic servomechanism, it is necessary to investigate these two methods in detail. In this study, the latter method, that is the method of utilizing an analog adaptive controller, was investigated. Since an analog adaptive controller does not discretize continuous signals and can perform real time calculation of the adaptive law, the computing time of the analog adaptive controller is theoretically zero.

In this study, at first, the adaptive law was constructed in continuous time description. Secondly, a CAD program for an analog adaptive controller was programed. Using this CAD program, fundamental design data of the controller were obtained. At last, experiments were conducted by use of an oilhydraulic servomechanism with an analog adaptive controller realized by an analog electronic circuit.

CONTINUOUS-TIME ADAPTIVE LAW

In this chapter, the adaptive law is constructed in continuous time description. A schematic diagram of an oilhydraulic servomechanism is presented in Fig.2.1. The object of this servomechanism is to control position of a mass-load (1). Position and velocity of the load are detected by a potentiometer (4) and a velocity transducer (5). Using these signals, an adaptive controller (6) performs calculations of the control law. The output signal of the controller is fed to a servo amplifier.

Then a servo valve (3) controls oil flow and a symmetrical cylinder (2) moves a mass-load. In this investigation, it is assumed that the transfer characteristics between input signal fed to a servo amplifier and load velocity can be approximated by a first order lag system and transfer characteristics of this system change or are not known. Then the adaptive control theory is applied to the block of the first order lag system. Therefore the servo system becomes the position feedback system containing the adaptive control system for load velocity.

The transfer function between input signal fed to a servo amplifier and load velocity is written as

$$\frac{V}{U}(s) = \frac{b}{s + a} \quad (1)$$

Adding a positive feedback compensation block of gain K_1 and an input signal compensation block of gain K_2 to the first order lag system Eq.(1), the block diagram of the compensated system becomes as shown in Fig.2.2. The input signal of the system is position error signal e . The transfer function of this system is written as

$$\frac{V}{E}(s) = \frac{K_2 b}{s + (a - K_1 b)} \quad (2)$$

A reference model is presented as

$$\frac{V_M}{E}(s) = \frac{b_M}{s + a_M} \quad (3)$$

Fig.2.1 Schematic diagram of an electro-hydraulic servomechanism

Fig.2.2 Block diagram of the compensated system

Parameters a and b are linearized parameters of the plant. If these parameters are known and constant, gains K_1 and K_2 can be designed as follows so that load velocity can follow reference model velocity signal;

$$K_1 = \frac{a - a_M}{b}, \quad K_2 = \frac{b_M}{b}. \quad (4)$$

But linearized parameters a and b of a real oilhydraulic servomechanism are not constant or unknown. Therefore the design of K_1 and K_2 according to Eq.(4) may not be carried out or may cause insufficient control results. In such a case, the adaptive control theory becomes a necessary and effective control method.

The adaptive control law is constructed in continuous time description. The control law becomes as follows (5),(7). The total block diagram of the adaptive control system is presented in Fig.2.3.

• position error

$$e = r - K_Y y \quad (5)$$

• velocity error

$$e_v = v - v_M \quad (6)$$

• signal fed to a servo amplifier

$$u = K_1 v + K_2 e \quad (7)$$

• adaptive laws of gains K_1 and K_2

$$K_1 = -\gamma_1 \int_0^t v e_v dt + K_{10} \quad (8)$$

$$K_2 = -\gamma_2 \int_0^t e e_v dt + K_{20} \quad (9)$$

($\gamma_1, \gamma_2 > 0$)

It is demonstrated as follows that Eq.(8) and Eq.(9) are adaptive laws of gains K_1 and K_2 .

After obtaining inverse Laplace transform of Eq.(2) and Eq.(3) and calculating velocity error e_v , a differential equation for e_v is obtained;

$$\frac{d}{dt} e_v = -a_M e_v + b \theta^T \zeta, \quad (10)$$

where

$$\begin{cases} \theta^T = [K_1 - \frac{a - a_M}{b}, K_2 - \frac{b_M}{b}] \\ \zeta^T = [v, e] \end{cases} \quad (11)$$

Differentiating Eq.(8) and Eq.(9), and arranging by use of Eq.(11), the following

equation is obtained¹;

$$\frac{d}{dt} \theta = -\Gamma \zeta e_v. \quad (12)$$

Γ is an adaptive gain matrix;

$$\Gamma = \begin{bmatrix} \gamma_1 & 0 \\ 0 & \gamma_2 \end{bmatrix}. \quad (13)$$

By the fact that the following function Eq.(14) is a Liapunov function, it is demonstrated that the simultaneous differential equation system Eq.(10) and Eq.(12) is a stable system.

$$F_L = \frac{1}{2} e_v^2 + \frac{1}{2} b \theta^T \Gamma^{-1} \theta \quad (14)$$

Since the simultaneous differential equation system Eq.(10) and Eq.(12) is stable, one of state variables, velocity error e_v , converges zero as time approaches infinity. Therefore load velocity v can follow reference model velocity signal v_M . It has been demonstrated that Eq.(8) and Eq.(9) are adaptive laws of gains K_1 and K_2 .

As evident from Eq.(5)~(9), the adaptive law constructed in continuous time description contains addition, subtraction, multiplication and integral. The adaptive

Fig.2.3 Block diagram of the adaptive control system

¹ Eq.(12) holds when a and b are time invariant. Linearized parameters a and b of the system treated in this study are time variant parameters. But, when computing speed of the control law is much faster than the speed of change of a and b , Eq.(12) is considered to hold.

law constructed in discrete time description contains division (1)~(5). On the contrary, the continuous-time adaptive law does not contain division. This becomes a considerably favorable merit for designing an adaptive controller.

DESIGN OF AN ANALOG ADAPTIVE CONTROLLER

In the above chapter, the adaptive law was constructed in continuous time description. In this chapter, an analog adaptive controller which is realized by an analog electronic circuit is designed. In design of an analog adaptive controller, the design process was divided into two processes. In the first process, from simulations based on the block diagram of the adaptive control system presented in Fig.2.3, reference model parameters a_M and b_M and adaptive gains γ_1 and γ_2 were determined. Simulations were performed considering flow characteristics of a servo valve, oil compressibility and saturation characteristics of a servo amplifier etc.. Transient responses were obtained from numerical calculations of equations of motion of a servomechanism by the Runge-Kutta method. In the second process, simulations were performed based on an analog electronic circuit of an adaptive controller. Resistances and condensers were designed.

In order to design an analog adaptive controller, simulations must be done repeatedly for various parameters of the controller. In this study, for simulations and design, a CAD program of an analog adaptive controller was programmed on NEC PC9801VX by use of a language of Turbo Pascal. In this CAD program, input and change of parameters of a servomechanism and an analog electronic circuit are possible and two kinds of the above mentioned simulations can be performed. And also frequency responses of the servo system only with feedback control, without adaptive control, can be calculated. Frequency responses of the feedback control system are useful data for determining reference model parameters.

Before starting design processes, specifications of the servo system were inputted to the CAD program. As presented in Fig.2.1, an oil-hydraulic servomechanism to be treated in this study consisted of a symmetrical cylinder, a servo valve and a mass-load. A symmetrical cylinder was $6.4 \times 10^{-4} \text{ m}^2$ in pressure exerted area and 150 mm in piston stroke. A servo valve was a model 3F-30L (Tokyo Precision Instruments Co., Ltd.). Specified supply pressure of the servo valve was 14MPa, specified flow rate was $5 \times 10^{-4} \text{ m}^3/\text{s}$ and specified input current

was 30 mA. As a mass-load, several iron boards which were bolted up and attached to a cylinder rod were used. Four ball bearings were used as wheels of the mass-load. Mass of the load was able to be selected from about 20kg to 60kg according to number of iron boards bolted up. Gain of a potentiometer was 300V/m and gain of a velocity transducer was 11.8V/(m/s). Supply pressure was set at 5MPa by a relief valve.

In the first process of design, reference model parameters and adaptive gains were determined as follows. When the adaptive control is perfectly performed and load velocity completely follows reference model velocity signal, transfer characteristics of the adaptive control system perfectly match those of the reference model. Then a block diagram of the servo system on such a condition can be written as Fig.3.1. Reference model can be designed based on the block diagram Fig.3.1. The transfer function of the closed loop system presented in Fig.3.1 is written as

$$\begin{aligned} \frac{Y}{R}(s) &= \frac{1}{K_Y} \cdot \frac{K_Y b_M}{s^2 + a_M s + K_Y b_M} \\ &= \frac{1}{K_Y} \cdot \frac{\omega_n^2}{s^2 + 2\zeta \omega_n s + \omega_n^2} \end{aligned} \quad (15)$$

where

$$\omega_n = \sqrt{K_Y b_M}, \quad \zeta = \frac{a_M}{2\sqrt{K_Y b_M}} \quad (16)$$

Arranging Eq.(16), a_M and b_M can be written as

$$a_M = 2\zeta \omega_n, \quad b_M = \frac{\omega_n^2}{K_Y} \quad (17)$$

Using Eq.(17), reference model parameters a_M and b_M can be determined from natural angular frequency ω_n and damping ratio ζ which are specified by servo system designers. To specify natural angular frequency and damping ratio, transfer characteristics of the position feedback control system without the adaptive control are able to be utilized as reference

Fig.3.1 Block diagram for design of reference model

data. Frequency responses were calculated using a linearized mathematical model of the servo system. Approximating frequency responses by that of a second order lag system, it was estimated that natural angular frequency was about 80rad/s (13 Hz) and damping ratio was about 0.8. Desired transfer characteristics were designed better. In this study, desired natural angular frequency ω_n was designed as 170rad/s (27Hz) and desired damping ratio ζ was designed as 0.5. Substituting these values to Eq.(17), reference model parameters were obtained;

$$a_M = 228.0 \text{ s}^{-1}, \quad b_M = 120.3 \text{ m}/(\text{V} \cdot \text{s}^2) \quad (18)$$

Using these values of reference model parameters, simulations based on the adaptive control system presented in Fig.2.3 were conducted. From simulated results for various adaptive gains, it was determined that $\gamma_1 = 0.01$ and $\gamma_2 = 10.0$.

In the second process of design, an analog electronic circuit was designed. In Fig.3.2, an analog electronic circuit which realizes the adaptive law is presented. Triangle symbols in Fig.3.2 represent operational amplifiers (LM318) and pentagonal symbols represent analog multipliers (ICL8013). In this figure, some values of resistances and condensers are specified. Other resistances whose values are not specified have a value of 10 k Ω . A position demand signal is fed to a terminal ① and a position signal of a load detected by a potentiometer is fed to a terminal ②. A velocity signal detected by a velocity transducer is fed to a terminal ③. A signal ④ is the output signal of a low-pass filter which represents transfer

characteristics of a reference model. Using high accurate variable resistances, reference model parameters are able to be adjusted. A signal ⑤ corresponds to a velocity error signal. Signals ⑥ and ⑦ are outputs of adaptive mechanisms consisted of multipliers, integrators (A and B) and variable gain amplifiers. These blocks correspond to adaptive laws of gains K_1 and K_2 (Eq.(8) and Eq.(9)). Adaptive gains are able to be turned by variable resistances. Signal ⑧ is fed to a servo amplifier.

Generally, voltage of a signal in an analog electronic circuit is limited by about supply voltage. The limit voltage of the circuit used was $\pm 13\text{V}$. And the limit voltage of input and output signal of an analog multiplier was $\pm 10\text{V}$. Resistances and condensers must be designed so that signal voltage should not exceed these limit voltages. In Fig.3.3, simulated results of transient responses of the adaptive control system with the analog adaptive controller are presented. It was confirmed that any signal did not exceed limit voltages. Since the signal corresponding to velocity error almost converged to zero, it has been cleared that the adaptive control was almost completely performed.

Computing time of an analog electronic circuit is theoretically zero. But, when designing a real circuit, it is necessary to examine frequency band width of an operational amplifier circuit and an analog multiplier. Band width of an integral circuit used for experiments was 0.08~320Hz. That of an addition or subtraction circuit was DC~15MHz. And that of an multiplier was DC~10kHz. Comparing with frequency region of transient responses of the servo system, these band width of

Fig.3.2 An analog electronic circuit of the analog adaptive controller

analog circuits were wide enough.

EXPERIMENTS

In this chapter, experiments on an oilhydraulic servo system with the analog adaptive controller are described. The servomechanism used for experiments has been mentioned in the above chapter.

Fig.3.3 Simulated results of the adaptive control system

Fundamental circuit of the analog adaptive controller has been presented in Fig.3.2. To this fundamental circuit, some optional circuits were added. One of these optional circuits was a reset circuit of integral circuits. Switching a toggle button in the reset circuit, two condensers of integral circuits were shorted and integral circuits were initialized. Initializing integral circuits corresponded to setting gains K_1 and K_2 to those initial values K_{10} and K_{20} . Switching the toggle button to the original position, integral circuits began to operate and calculations of the adaptive law started. In the beginning of experiments, integral circuits were initialized and sine or step signals were fed to the system as position demand signal. When the toggle button was

Fig.4.1 Experimental results of step responses

switched, the adaptive control started. Transient signals of the system were recorded by a microcomputer NEC PC9801F with an A/D converter of 12 bit. Sampling interval of the A/D was 5 ms.

In Fig.4.1, experimental results of step responses of the adaptive control system are presented. In the beginning of

experiments, integral circuits were initialized. After switching a toggle button and starting the adaptive control, the system showed considerably good step responses. Load velocity signal followed reference model velocity signal.

In Fig.4.2, experimental results of transient responses to sine input signal of 15Hz are presented. In this figure, adaptive gain signals are also presented. Adaptive gain signals are signals ⑥ and ⑦ in Fig.3.2 (these signals correspond to K_1 and K_2). After start of the adaptive control, these adaptive gain signals began to change and showed stationary responses in 0.4s. Then load velocity signal followed reference model velocity signal. Since desired natural frequency ω_n was 170rad/s

Fig.4.2 Experimental results of transient responses to sine input signal of 15Hz

Fig.4.3 Experimental results of transient responses to sine input signal of 30 Hz

(27Hz) and desired damping ratio ζ was 0.5, the adaptive control system was able to show good position responses to sine input signals of 15Hz. In experiments, transient responses of the system to sine input signals of 30Hz were also tested. These experimental results are presented in Fig.4.3. Just after starting the adaptive control, the system showed stable and stationary responses. And load velocity signal followed reference model velocity signal. In experiments of the discrete-time adaptive control with a microcomputer using the same servo mechanism used in this study, the system was not able to show stable responses to such a relatively high frequency input signal. Since the computing time of the analog adaptive controller is theoretically zero, the continuous-time adaptive control system can show good responses to such a high frequency input signal.

CONCLUSION

In this study, an analog adaptive controller was investigated. At first, the adaptive law was constructed in continuous time description. Secondly, a CAD program for design of the controller was programmed and an analog electronic circuit which realized the adaptive law was designed from various simulations. At last, experiments of the servo system with the analog adaptive controller were conducted. And it has been cleared that the analog adaptive control system showed stable and good responses to step input signals and sine input signals of relatively high frequency.

From investigation of band width of the analog adaptive controller, it is obvious that this controller can compute considerably higher frequency signals. Therefore investigation of the servo system consisted of a high speed oilhydraulic servomechanism and the analog adaptive controller is now being planned by the authors.

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