Observer-Based Time-Delay Control of a Four-Cylinder Electrohydraulic Servosystem* (Controller Design)

Yuh CHENG** and Chuen-Bor LEE**

Synchronizing control of a four-cylinder electrohydraulic servosystem is considered in this paper. For simplification of design, the system is separated into four subsystems, which track the same output signal of a reference model. The interaction forces among the four cylinders are considered as disturbance forces and the time delay control scheme is used here to estimate the disturbance force and unknown system dynamics. For reducing the sensor noise in controller design, the observed state variables are used in place of the numerical differentiated ones. The feasibility of the proposed control strategies is verified via experimental studies in this paper and the stability of this closed-loop system is proved in Part II.

Key Words: Time-Delay Control, Observer, Synchronizing Control, Electrohydraulic Servosystem

1. Introduction

Heavy-duty hydraulic equipments such as presses, rolling mills, shearing and bending machines are usually actuated by two or more hydraulic cylinders. It is expected to synchronize the movement of these cylinders. However, cylinders synchronization will not be guaranteed because of the difference in seal friction, internal leakage, machining tolerance as well as load resistance of cylinders. It has been established that the hydraulic cylinders can not be synchronized precisely by means of open-loop control over a large number cycles of operation. Greater accuracy can be achieved by using a servosystem. Zhang et al. proposed a model reference adaptive synchronizing control strategy utilizing the "master-slave" approach for the synchronization of two hydraulic cylinders. Tomizuka et al. presented a synchronizing controller to control the speed of two dc motors under adaptive feedforward control. All the above mentioned papers focus on the synchronization of two actuators. The synchronization of four hydraulic cylinders is studied in this paper.

To simplify the controller design, the four-cylinder electrohydraulic servosystem is regarded as four subsystems and the valve controlled cylinder of each subsystem is described by a first order model. The four subsystems track the same output signal of a reference model and the synchronization error will be reduced. However, the interaction forces among the four cylinders, and the unknown system dynamics will cause the deviation from synchronization. The time-delay control strategy is adopted here to improve the synchronization accuracy.

2. System Model

Figure 1 displays the schematic diagram of the experimental setup. The dimensions and the component parameters of this experimental setup are listed in Table 1 and Table 2. A rectangular thick steel plate is suspended by four extensible props. Each prop is actuated by a servo hydraulic cylinder. A rotator with an eccentric load is installed on the plate, which can be used to alter the gravity center of the plate and enlarge the difference among the load resistance of the four valve-controlled hydraulic cylinders. The displacements of the four props are sensed by four potentiometers separately. The outputs of the potentiometers are fed back via a 12-bit A/D
converter to form a closed-loop system. The control algorithms are programmed in Turbo C language on a 486 personal computer. A 12-bit D/A converter, with sensitivity of 4.88 mv/bit, is used to output the processed control signals to the servo amplifiers. For simplification of the synchronizing controller design, each servo hydraulic cylinder is considered as a subsystem. The in-istent and coupled forces among the four subsystems are considered as uncertainty and disturbance, which may be complemented by the observer-based time-delay control scheme.

The individual servo hydraulic cylinder system can be described as the following third-order linear system.

\[ Y(s) = \frac{Kv_0 \omega_n^2 U(s) + D(s)}{s^3 + 2\xi \omega_n s + \omega_n^2}. \]  \hspace{1cm} (1)

where \( Y \) is the piston displacement, \( Kv_0 \) is the steady state speed gain, \( U \) is the control effort, \( D \) is the external force composed of load weight, friction force and interaction force, \( \xi \) is the damping ratio, \( \omega_n \) is the natural frequency, the subscript \( i = 1, 2, 3, 4 \) denotes the cylinder number.

The position transducer used in this system are potentiometers, their outputs are deeply affected by the noise signal. Therefore, in order to get rid of using high order state variables in the controller design, the system model is reduced to a first order form by rearranging Eq. (1) as:

\[ sY(s) = -\left( \frac{s^3}{\omega_n^2} + \frac{2\xi s^2}{\omega_n} \right) Y(s) + K_v U(s) + D(s). \]  \hspace{1cm} (2)

where \( D = D_0/\omega_n^2 \).

Defining \( F(s) = -\left( \frac{s^3}{\omega_n^2} + \frac{2\xi s^2}{\omega_n} \right) \),

then

\[ sY(s) = F(s) Y(s) + K_v U(s) + D(s). \]  \hspace{1cm} (3)

where \( F(s) Y(s) \) includes the high order variables of the system. In the time-delay controller design, this term and the external force can be estimated and compensated into the control effort.

By putting Eq. (4) into state equation form

\[ \dot{x}(t) = K_v u(t) + f(x, t) + d(t), \]  \hspace{1cm} (5)

\[ y(t) = x_1(t), \]  \hspace{1cm} (6)

where \( y, u, f, d \) are the inverse Laplace transformation of \( Y, U, F, Y, D \) respectively, and \( x_i \) is the state variable.

### 3. Control Algorithms

A reduced order system is described as

\[ \dot{x} = f(t, t) + B(x, t) u + d(t). \]  \hspace{1cm} (8)

where \( x \in \mathbb{R}^r \) denotes the state vector, \( f(t, t) \in \mathbb{R}^r \) denotes the unknown system dynamics vector, which includes nonlinearities, uncertain dynamics and high order dynamics of the system, \( B(x, t) \in \mathbb{R}^{rs} \) denotes the control distribution matrix with known variation ranges which can be determined via the experiment, \( u \in \mathbb{R}^p \) denotes the control vector, \( d(t) \in \mathbb{R}^r \) denotes the disturbance vector.

### Table 1 Dimensions of experimental setup

<table>
<thead>
<tr>
<th>Steel plate length</th>
<th>1.6 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>width</td>
<td>1.0 m</td>
</tr>
<tr>
<td>thickness</td>
<td>25 mm</td>
</tr>
<tr>
<td>Rotator disk radius</td>
<td>400 mm</td>
</tr>
<tr>
<td>thickness</td>
<td>50 mm</td>
</tr>
<tr>
<td>Eccentric load mass</td>
<td>200 kg</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>300 mm</td>
</tr>
<tr>
<td>Prop length</td>
<td>800 mm</td>
</tr>
<tr>
<td>Hydraulic cylinder stroke</td>
<td>750 mm</td>
</tr>
<tr>
<td>bore diameter</td>
<td>40 mm</td>
</tr>
<tr>
<td>rod diameter</td>
<td>20 mm</td>
</tr>
</tbody>
</table>

### Table 2 Component parameters of experimental setup

<table>
<thead>
<tr>
<th>Servo valve</th>
<th>input current</th>
<th>10 mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOWTY 4653</td>
<td>rated flow</td>
<td>5 l/min at 7 MPa</td>
</tr>
<tr>
<td></td>
<td>null leakage</td>
<td>0.1 l/min at 14 MPa</td>
</tr>
<tr>
<td></td>
<td>bandwidth</td>
<td>90 Hz for rated flow 5 l/min</td>
</tr>
<tr>
<td></td>
<td>hysteresis</td>
<td>&lt;3% without dither</td>
</tr>
<tr>
<td></td>
<td>threshold</td>
<td>&lt;1% without dither</td>
</tr>
<tr>
<td></td>
<td>null shift</td>
<td>&lt;2% for temp. change 40°C</td>
</tr>
<tr>
<td>Potentiometer</td>
<td></td>
<td>&lt;2% for supply pressure change 80%–110%</td>
</tr>
<tr>
<td>KEEN-TECH</td>
<td>linearly</td>
<td>&lt;0.07%</td>
</tr>
<tr>
<td>KTC75</td>
<td>resistance</td>
<td>2.5 KΩ ±20%</td>
</tr>
<tr>
<td>D/A converter</td>
<td></td>
<td>resolution 12 bits</td>
</tr>
<tr>
<td>ADVENCH</td>
<td>linearly</td>
<td>±1/2 bit</td>
</tr>
<tr>
<td>PCI276</td>
<td>settling time</td>
<td>30 msec</td>
</tr>
<tr>
<td>A/D converter</td>
<td></td>
<td>resolution 12 bits</td>
</tr>
<tr>
<td>ADVENCH</td>
<td>linearly</td>
<td>±1 bit</td>
</tr>
<tr>
<td>PCL812</td>
<td>conversion</td>
<td>30 KHz</td>
</tr>
<tr>
<td>speed</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A stable linear time invariant reference model is defined as
\[ \dot{x}_r = A_x x_r + B_x r. \]  
(9)
where \( x_r \in \mathbb{R}^x \) denotes the state vector of the reference model, \( A_x \in \mathbb{R}^{x \times x} \) denotes the system matrix, \( B_x \in \mathbb{R}^{x \times p} \) denotes the command distribution matrix, and \( r \in \mathbb{R}^p \) denotes the command vector.
Let the model tracking error vector be defined as
\[ e = x_x - x. \]  
(10)
The tracking error is required to disappear with the error dynamics of
\[ \dot{e} = A_x e. \]  
(11)
Rearranging Eq. (8) as
\[ \dot{x} = \dot{f}(\cdot, t) + B_u u, \]  
(12)
where \( B \) is the constant matrix located in the variation range of \( B(x, t) \), \( \dot{f}(\cdot, t) \) is expressed as
\[ \dot{f}(\cdot, t) = f(\cdot, t) + (B(x, t) - B)u + d(t), \]  
(13)
which includes the total effect of the unknown system dynamics and disturbance. Subtracting Eq. (12) from Eq. (9) and yields
\[ \dot{e} = A_x e + (-\dot{f}(\cdot, t) + A_x x + B_x r - B u) \]  
(14)
Substituting Eq. (11) into Eq. (14) and rearranging to get
\[ \dot{B} u = -\dot{f}(\cdot, t) + A_x x + B_x r. \]  
(15)
If the matrix \( B \) is not a square matrix, the control effort \( u \) is approximately described as
\[ u = B^*(-\dot{f}(\cdot, t) + A_x x + B_x r) \]  
(16)
where \( B^* \) is defined as \( B^* = (B^T B)^{-1} B^T \) so that \( B^* B = I \).
In order to estimate \( f(\cdot, t) \), the time-delay control adopts an efficient method which assumes that the variations of the unknown system dynamics and disturbance are not very large in a short time step, so
\[ \dot{f}(\cdot, t) \approx \dot{f}(\cdot, t - \tau). \]  
(17)
As long as time step \( \tau \) is sufficiently short, the above equation is then tenable. In this paper \( \tau \) is selected as the same value as the sampling interval. The system uncertainty is estimated as
\[ \dot{f}(\cdot, t) = \dot{x}(t) - \dot{B} u(t) \approx \dot{x}(t - \tau) - \dot{B} u(t - \tau). \]  
(18)
Substituting Eq. (18) into Eq. (16) yields the time-delay control law as
\[ u = B^*[\dot{x}(t - \tau) - \dot{B} u(t - \tau) + A_x x + B_x r]. \]  
(19)

4. Observer Design

With the output vector of \( y \in \mathbb{R}^y \) and the output distribution matrix of \( C \in \mathbb{R}^{y \times r} \) the system is given as
\[ \dot{x} = f(\cdot, t) + B(x, t)u + d(t), \]  
(20)
\[ y = Cx. \]  
(21)
The observer is designed by using the linearized time invariant system model and is expressed as
\[ \dot{z} = Az + Bu + L(y - \hat{y}), \]  
(22)
\[ \hat{y} = Cz. \]  
(23)
where \( z \in \mathbb{R}^r \) denotes the observed state vector of \( x \), \( y \) denotes the observed output vector of \( y \), \( \hat{A} \) and \( \hat{B} \) denote the approximations of the linearized time invariant system matrix and control distribution matrix, respectively, which can be obtained by the experiment. \( L \in \mathbb{R}^{y \times q} \) denotes the gain matrix of the observer. Then the time-delay control law with the observed state variables becomes
\[ u = \hat{B}^*[\dot{z}(t - \tau) - \dot{B} u(t - \tau) + A_n z + B_n r]. \]  
(24)

5. Observer-Based Time-Delay Synchronizing Controller Design

The reduced-order models of the individual servo hydraulic cylinder subsystem described in section 2 are repeated here.
\[ \dot{x}_i(t) = K_v u_i(t) + f_i(\dot{x}_i, \dot{z}_i) + d_i(t), \]  
(25)
\[ y_i(t) = z_i(t), \quad i = 1, 2, 3, 4 \]  
(26)
The first order reference model is expressed as
\[ \dot{x}_n = -\lambda_n x_n + \lambda_n r, \]  
(27)
with pole at \( s = -\lambda_n \). The observers for each subsystem are
\[ \dot{z}_i = \hat{K}_v u_i + l(y_i - \hat{y}_i), \]  
(28)
\[ \hat{y}_i = z_i. \]  
(29)
where \( \hat{K}_v \) is the steady-state speed gain obtained from experiment. The pole of the observer is located at \( s = -l \). The control laws with the observed state variables are
\[ u_i = -\frac{1}{\hat{K}_v} \left[ \dot{z}_i(t - \tau) + \hat{K}_v u_i(t - \tau) - \lambda_n z_i + \lambda_n r \right], \]  
(30)
\[ i = 1, 2, 3, 4 \]

6. Experimental Study

The experimental studies were performed to evaluate the performance of the proposed control strategy developed for the four-cylinder hydraulic system synchronizing control. The time-delay control effort is expressed as Eq. (30).
For comparison this control strategy is compared to a model reference control without time-delay unknown system dynamics and disturbance compensation which is expressed as
\[ u_i = -\frac{1}{\hat{K}_v} \left[ \dot{z}_i(t - \tau) + \hat{K}_v u_i(t - \tau) - \lambda_n z_i + \lambda_n r \right]. \]  
(31)
A square-wave command signal and a segmental line command signal are used to test the control performance. The segmental line signal is composed of several linked straight lines, which is similar to the command signal used for presses, consisting of the process of high speed lowering, low speed lowering, stop, high speed lifting and low speed lifting signals.
The steady-state speed gain is \( \hat{K}_v = 1 \). The pole of the first-order reference model is at \( s = -\lambda_n \). Because the rise time of the step response for a first
order system is \( t_r = 2.2/\lambda_n \). Selecting \( t_r = 1.5 \text{ sec} \) for the control with a square-wave command signal, then yields \( \lambda_n = 1.5 \). For the control with command signal of a segmental line, a value of \( \lambda_n = 10 \) was selected to get faster response. The delay time \( r \) taken as the same as the sampling interval of 20 ms was used in this study.

First of all, the performance of using a numerical differentiator and an observer in the time-delay control law is compared in terms of the displacement response of the first hydraulic cylinder and the control effort as shown in Fig. 2. These results indicate that although both cases have similar response, the controller with a numerical differentiator is more affected by the noise, so the control effort is chattering obviously. On the contrary, the controller with an observer is insensitive to the influence of noise, but there is slight phase lag as command is varied rapidly.

The pole of the observer is at \( s = -l \), it will affect the accuracy of the state variables estimation, in turn, the synchronizing control performance of the four hydraulic cylinders. To choose a suitable value of \( l \), a number of experiments were made by changing the \( l \) value. Figure 3 presents the step response of the four-cylinder electrohydraulic servosystem for different values of the observer parameter \( l \). Figure (a) shows the displacements of the four cylinders at \( l = 1 \). Figure (b) is that for \( l = 15 \). It can be seen that the value of \( l \) should be large for obtaining a satisfactory synchronization. This is because the estimated state variables are close to the real ones, in turn, the unknown system dynamics and disturbance force are estimated and implemented more precise. As a consequence, the synchronization error is reduced. However if the value of \( l \) is too large, the system response will present the phenomenon of oscillation.

Figure 4 shows the displacement responses and synchronization errors to a square-wave input of frequency 0.125 Hz with amplitude of 2 cm for
variation of supply pressure $P_s$. Figure (a), (c) show the displacement of the first cylinder for supply pressure 8 MPa and 6 MPa, respectively. Figure (b), (d) show the synchronization error between the first and the second cylinders (the most asynchronous pair) for supply pressure 8 MPa and 6 MPa, respectively. Comparing these figures, it reveals that the synchronizing control performance of the MRC (model reference control) is more influenced by the disturbance force and unknown dynamics of the system at a lower supply pressure of 6 MPa. OBTDC (observer-based time-delay control) gives almost the same system dynamics irrespective of the variation of the supply pressure. It means that the OBTDC approach can complement the uncertainty of $K_{ne}$ and the coupled force, so it is nearly able to achieve good synchronizing control performance.

Figure 5 presents the comparison of the performance of the OBTDC and the MRC to a segmental line command signal. Figure (a) shows the displacement responses. Figure (b) shows the synchronization error between the first cylinder and the second one. This result indicates that the OBTDC approach still achieve a better control performance than that of the MRC approach.

7. Conclusions

An observer-based time-delay controller has been designed and applied to the synchronizing control of a hydraulic system actuated by four servo-cylinders. A first order system model was adopted to derive a simple structure controller for shortening the computation time, which makes the controller suitable for controlling the multi-actuator hydraulic system. Besides, an observer was adopted to estimate the state variables instead of using the numerical differentiator to prevent the influence of the noise. The experimental results indicate that the observer-based time-delay control system is insensitive to parameter variation in comparison to the model reference control system. Such trend can be explained as that the proposed OBTDC approach can complement
the unknown system dynamics and the coupled forces of the four hydraulic cylinders to obtain a better synchronizing control performance.

References


