Adaptive Sliding Mode Control of Artillery Coordinator
Based on Disturbance Observer

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Abstract: In order to improve the control accuracy of the artillery coordinator composed of
hydraulic servo system under various uncertain conditions such as extreme environment,
unknown disturbances, and system parameter changes, an adaptive sliding mode control
strategy based on disturbance observer is designed. Sliding mode control can make the system
follow the designed sliding mode dynamic surface state trajectory, and realize the control of
non-linear system. Increasing adaptive control can prevent system failure due to excessive
sliding mode switching gain. Based on this, disturbance observers are added, feed-forward
compensation is performed, and the influence of system parameters and load torque changes on
the system is reduced to reduce chattering and effectively improve control performance. The
electro-hydraulic joint simulations show that the algorithm can make the system meet the
control requirements under complex working conditions under different coordination angles,
ammunition and no-load conditions.

1. Introduction
The characteristics of sliding mode variable structure control are suitable for non-linear control, which
has little influence on interference and parameter changes, and is easy to implement. Suitable for
electro-hydraulic servo system control. However, the actual system is non-ideal. The state trajectory
will pass back and forth on the sliding mode surface, causing jitter, which will affect the state and
control accuracy of the system. Chattering is an inevitable problem for sliding mode variable structure
control [1-2]. Adaptive control: It can identify the dynamic characteristics of the object and take
decisions to change the system action [3-4]. The disturbance observer does not need to establish an
accurate mathematical model, and has a simple structure and strong engineering usability.
Feed-forward compensation for unknown parameters and unmodeled states of the system can
effectively reduce the chattering of the sliding mode controller, improve the stability and robustness of
the system, and enhance the anti-interference ability of the system [5].

Based on the study of sliding mode control, adaptive control and perturbation observer algorithm,
based on the study and inspiration of the above literature, this paper designs a perturbation observer
based on the problem of artillery coordinator control with slow time-varying perturbations. Adaptive
sliding mode control. DOB is used to feed forward the system disturbance to compensate for changes
in system parameters and load torque. The unknown parameter is not prevented from being
over-estimated. By introducing adaptive rate estimation parameters, the chattering of sliding mode
control is greatly reduced, and the feasibility of the control scheme is verified by the joint simulation
of AMEsim and MATLAB [6].
2. System description and modeling

The actuator of the coordinator is a single-rod cylinder, which is controlled by a servo valve and an electrical system. It is a typical electromechanical-hydraulic structure. As shown in Figure 1, the coordinator is fixed at point B, the coordination cylinder is connected to the coordinator through a hinge C, and the lower fulcrum of the cylinder is point A. The angle is the rotation angle of the coordinator. The angle between the oil cylinder and the coordinator is. Is the angle between AB and vertical = 62 \degree

![Figure 1. Coordinator system diagram.](image)

The inlet pressure of the hydraulic system is $P_p$, the return pressure is $P_t$, the flow rate of the rodless cavity is $Q_1$, the area is $A_1$, the pressure is $P_1$, the flow rate of the rod cavity is $Q_2$, the area is $A_2$, and the pressure is $P_2$. The controller receives a command and sends a signal to the servo valve based on the system's motion angle and the pressure in the two chambers of the cylinder $u$, and the core displacement is $X_t$,

$$X_t = k_t u$$  \hspace{1cm} (1)

Assuming 1: no leakage, the continuous flow equation of the coordinator cylinder is:

$$\begin{align*}
Q_1 &= A_1 \dot{x} + \frac{V_1}{\beta_e} \dot{P}_1 \\
Q_2 &= A_2 \dot{x} - \frac{V_2}{\beta_e} \dot{P}_2
\end{align*}$$  \hspace{1cm} (2)

where $A_1$ is the area of the cavity without a rod, $A_2$ is the area of the cavity with a rod, $\beta_e$ is the volume elastic modulus of the hydraulic oil, and $x$ is the displacement of the piston rod.

As shown in Figure (1), assuming that the driving force of the coordinator cylinder is $F$, it can be obtained from Newton's second law:

$$F l_{BC} \sin \alpha - m g l_{BD} \sin \theta = J_{eq} \ddot{\theta} + B_{eq} \dot{\theta} + d$$  \hspace{1cm} (3)
where \( m = 100 \text{kg} \) is the mass of the coordinator, \( g = 9.8 \text{m/s}^2 \), \( J_{eq} \) is the equivalent moment of inertia, \( B_{eq} \) is the equivalent viscous friction coefficient, and \( d \) is the unmodeled disturbance torque.

According to the force balance equation of the hydraulic cylinder:

\[
F = P_1A_1 - P_2A_2
\]  

(4)

define the state variables \( X = [\theta_1, \theta_2, \theta_3]^T = [\theta, \dot{\theta}, \ddot{\theta}]^T \). With (1)~(4), the system state can be expressed as follows:

\[
\begin{cases}
\theta_1 = \theta_2 \\
\theta_2 = \theta_3 \\
a_1\theta_3 = -a_2\theta_2 - a_3\theta_3 + u - d
\end{cases}
\]  

(5)

where \( a_1, a_2, a_3, d \) are uncertain parameters, so there are assumptions 2: Unknown parameters \( a_1, a_2, a_3, d \) bounded, \( a_{1\text{max}} > a_{1\text{min}} > 0 \), \( a_{2\text{max}} > a_{2\text{min}} > 0 \), \( a_{3\text{max}} > a_{3\text{min}} > 0 \), \( \eta > 0 \) make \( \theta_{1\text{min}} \leq \theta_1 \leq \theta_{1\text{max}} \), \( \theta_{2\text{min}} \leq \theta_2 \leq \theta_{2\text{max}} \), \( \theta_{3\text{min}} \leq \theta_3 \leq \theta_{3\text{max}} \), \( |d| < \eta \).

3. Controller design

The structure of the coordinator controller algorithm is shown in Figure (2). \( \theta_d \) is the target angle, \( \theta, \dot{\theta}, \ddot{\theta} \) is the actual angle, angular velocity, and angular acceleration. \( \hat{d} \) is the disturbance observer output.

\[\text{Figure 2. Control structure diagram.}\]

3.1. Design of Sliding mode controller

The angle tracking error and the sliding mode function are defined separately

\[
e = \theta_d - \theta
\]  

(6)

\[
s = \ddot{e} + y_1\dot{e} + y_2e
\]  

(7)

where \( y_1, y_2 \) is the sliding surface parameter to be designed, which can be determined according to the actual control situation.
Define the Lyapunov function

\[ V_1 = \frac{1}{2} a_i s \]  

\[ V_1 = sa_i \dot{s} \]

\[ = s \left[ -a_1 (\ddot{\theta}_d - y_1 \ddot{e} - y_2 \dot{e}) - a_2 \dot{\theta}_2 - a_3 \theta_3 + u - d \right] \]  

design the robust controller \( u \) as follows

\[ u = a_1 (\ddot{\theta}_d - y_1 \ddot{e} - y_2 \dot{e}) + a_2 \dot{\theta}_2 + a_3 \theta_3 - k_s s - \eta \cdot sat(s) \]  

where \( k_s \) is the robustness coefficient, \( \eta \) is the switching gain, \( sat(s) \) is a saturation function, the purpose is to reduce chattering

\[ sat(s) = \begin{cases} 
1, & s \Rightarrow \Delta \\
\frac{s}{\Delta}, & |s| \leq \Delta \\
-1, & s < -\Delta 
\end{cases} \]  

where \( \Delta \) is the thickness of the boundary layer.

With (8)–(11)

\[ \dot{V}_1 = s \left[ -a_1 (\ddot{\theta}_d - y_1 \ddot{e} - y_2 \dot{e}) - a_2 \dot{\theta}_2 - a_3 \theta_3 + u - d \right] 
\]

\[ = s \left[ -k_s s - \eta \cdot sat(s) - d \right] 
\]

\[ = -k_s s^2 - \eta \cdot |s| - ds \]

\[ \leq -k_s s^2 \]  

the system can stable by these functions.

### 3.2. Design of DOB

Define[7]

\[ \dot{\hat{d}} = K (d - \hat{d}) \]  

\[ z = \hat{d} + Ka \dot{\theta} \]

\[ \hat{z} = \hat{d} - Ka \hat{\theta} \]

\[ = K (a_i \ddot{\theta} - a_i \dot{\theta} + a_i \ddot{\theta}_d) - Ka \ddot{\theta}_d \]

therefore, DOB could be designed as follows

\[ \begin{cases} 
\dot{z} = K (a_i \dot{\theta} - a_i \ddot{\theta} + u) - K \hat{d} \\
\hat{d} = z - Ka \ddot{\theta}_d 
\end{cases} \]

Define the error of DOB as

\[ \tilde{d} = d - \hat{d} \]
assumption 3: \( \dot{d} = 0 \), derivative calculation for Equation (17)

\[
\dot{\hat{d}} = \dot{d} - \hat{d} = -\dot{\hat{z}} + Ka\hat{\theta}
\]  
(18)

Substitute equation (15) into (18)

\[
\dot{\hat{d}} = -K(-a_2\hat{\theta} - a_3\hat{\theta} + u + Ka\hat{\theta}) + Kz + Ka\hat{\theta}
\]

\[
= K(z - Ka\hat{\theta}) - K(-a_2\hat{\theta} - a_3\hat{\theta} + u + a_i\hat{\theta})
\]

\[
= K(\hat{d} - d)
\]

(19)

Therefore, the error equation of the DOB is \( \dot{\hat{d}} + K\hat{d} = 0 \), and the solution is \( \hat{d}(t) = \hat{d}(t_0)e^{-Kt} \), the value of \( \hat{d}(t_0) \) is determined, and the convergence accuracy of the observer depends on \( \hat{d} \), so that the estimated value approaches the interference \( d \) exponentially.

With the introduction of the DOB equation (16), the robust control law equation (10) becomes

\[
u = a_1(\hat{d} - s - y_1 - y_2) + a_2\theta_2 + a_3\theta_3 + \hat{d} - k_1s - s \cdot \text{sat}(s)
\]  
(20)

Define the Lyapunov function

\[
V_2 = \frac{1}{2}a_1s^2 + \frac{1}{2}\hat{d}^2
\]

(21)

\[
\dot{V}_2 = sa_1\dot{s} + \hat{d}\dot{\hat{z}}
\]

\[
= -k_1s^2 - \eta|s| - ds + (d - \hat{d})\dot{\hat{d}}
\]

\[
= -k_1s^2 - \eta|s| - ds - K\hat{d}^2
\]

(22)

\[
\leq -k_1s^2 - K\hat{d}^2 \leq -k_1(\frac{1}{2}a_1s^2 + \frac{1}{2}\hat{d}^2)
\]

\[
= -k_1V_2
\]

where \( k_2 = 2 \min(a_1k_3, K) \), the solution of the equation \( \dot{V}_2 \leq -k_1V_2 \) as follows[8]

\[
V_2(t) \leq e^{-k_1(t-t_0)}V(t_0)
\]  
(23)

It can be seen that the control system converges exponentially, and the convergence accuracy depends on the value \( k_1 \).

3.3. Design of adaptive control

In the actual control process, the value of \( a_1, a_2, a_3 \) is constantly changing and uncertain. Therefore, an adaptive algorithm is added on the basis of control law equation (20) to estimate parameter changes. Define the error of estimation as

\[
\tilde{a}_i = a_i - \hat{a}_i
\]  
(24)

where \( \tilde{a}_i \) is the estimation error, \( \hat{a}_i \) is the estimated value, \( i = 1, 2, 3 \).

Then equation (20) becomes
\[ u = \dot{\hat{a}}_1 (\ddot{q} - y_1 \ddot{e} - y_2 \dot{e}) + \dot{\hat{a}}_2 \theta_2 + \dot{\hat{a}}_3 \theta_3 + \dot{\hat{a}}_i - k_i s - \eta \cdot \text{sat}(s) \]  \quad (25)\\

define the Lyapunov function

\[ V_1 = V_2 + \frac{1}{2} c_1 \dddot{a}_1 + \frac{1}{2} c_2 \dddot{a}_2 + \frac{1}{2} c_3 \dddot{a}_3 \]  \quad (26)\\

\[ V_2 = V_2 + c_1 \dddot{a}_1 + c_2 \dddot{a}_2 + c_3 \dddot{a}_3 = s \left[ -\dddot{a}_1 (\ddot{q} - y_1 \ddot{e} - y_2 \dot{e}) - \dddot{a}_2 \theta_2 - \dddot{a}_3 \theta_3 - k_i s - \eta \text{sat}(s) - d \right] - K \dddot{a}^2 + c_1 \dddot{a}_1 + c_2 \dddot{a}_2 + c_3 \dddot{a}_3 \]  \quad (27)\\

where \( c_1, c_2, c_3 \) are positive numbers.

Assumption 4: \( \dot{a}_1 = 0, \dot{a}_2 = 0, \dot{a}_3 = 0 \).

Design the adaptive law as follows

\[
\begin{aligned}
\dot{\hat{a}}_1 &= -\frac{1}{c_1} s (\ddot{q} - y_1 \ddot{e} - y_2 \dot{e}) \\
\dot{\hat{a}}_2 &= -\frac{1}{c_2} s \theta_2 \\
\dot{\hat{a}}_3 &= -\frac{1}{c_3} s \theta_3
\end{aligned}
\]  \quad (28)\\

substitute equation (28) into equation (27)

\[ V_3 = \hat{a}_1 \left[ c_1 \dddot{a}_1 - s (\ddot{q} - y_1 \ddot{e} - y_2 \dot{e}) \right] + \hat{a}_2 (c_2 \dddot{a}_2 - s \theta_2) + \hat{a}_3 (c_3 \dddot{a}_3 - s \theta_3) - k_i s^2 - \eta \left| s \right| - ds - K \ddot{a}^2 \]

\[ \leq -k_i s^2 - K \ddot{a}^2 \]  \quad (29)\\

the system can stable by these functions.

In order to prevent the overestimation of \( \hat{a}_1, \hat{a}_2, \hat{a}_3 \) from affecting the system and ensuring its bounds, a discontinuous projection algorithm is used [9]

\[
\dot{\hat{a}}_i = \text{Proj}_{a_i} \left( \frac{1}{c_i} \beta_i \right) = \begin{cases} 
0, & \hat{a}_i \geq a_{i,\text{max}} \text{and} \frac{1}{c_i} \beta_i > 0 \text{and} \frac{1}{c_i} \beta_i > 0 \\
0, & \hat{a}_i \leq a_{i,\text{min}} \text{and} \frac{1}{c_i} \beta_i < 0 \text{and} \frac{1}{c_i} \beta_i < 0
\end{cases} \quad (30)\\

\]

where \( i = 1, 2, 3 \), \( \beta_1 = -s (\ddot{q} - y_1 \ddot{e} - y_2 \dot{e}) \), \( \beta_2 = -s \theta_2 \), \( \beta_3 = -s \theta_3 \).

Assumption 5: equation \( a_{i,\text{min}} \leq \hat{a}_i (0) \leq a_{i,\text{max}} \) can satisfy equation \( a_{i,\text{min}} \leq \hat{a}_i (t) \leq a_{i,\text{max}} \) in any case, therefore, the modified algorithm can guarantee the boundedness of the estimated parameters.

4. The Co-simulation and Results
The electro-hydraulic servo simulation model is established by the AMESim and Simulink
co-simulation method to improve modelling efficiency and accuracy.

The parameters of the electro-hydraulic servo system: DOB gain $K=50$, sliding surface parameters $y_1=150$, $y_2=12000$, adaptive parameters $c_1=1\times10^{20}$, $c_2=1\times10^{13}$, $c_3=1\times10^{17}$, robust coefficient $k_s=abs(s)\times10^{-8}$, switching gain $\eta=15$, boundary layer thickness $\Delta=2\times10^4$, $a_{1\text{max}}=2\times10^{-7}$, $a_{1\text{min}}=-2\times10^{-7}$, $a_{2\text{max}}=4\times10^{-3}$, $a_{2\text{min}}=-2\times10^{-3}$, $a_{3\text{max}}=9\times10^{-5}$, $a_{3\text{min}}=-6\times10^{-5}$. Set the target angle to 66 degrees, the simulation step size is 0.001 seconds, and the simulation time is 3 seconds. The angle tracking trajectory is shown in Figure(3). The angle tracking error is shown in Figure(4).

The adaptive parameters at three different target angles are shown in Figure(5)~Figure(7). The DOB parameters at three target angles is shown in Figure(8).

It can be seen from Figures 3 and 4 that the traditional sliding mode control error has good tracking performance in the early stage, with a maximum dynamic error of -6°. When it reaches the target angle, the tracking error hovers around ±0.4°. Chatter, unable to position smoothly. The maximum
dynamic tracking error of the adaptive sliding mode control based on the DOB is -5 °, and the
dynamic error when reaching the target angle is ± 0.15 °. The in-position time is about 0.8 seconds,
and the chatter phenomenon is significantly weakened, which improves the positioning accuracy and
enables The coordinator smoothly and quickly locates to the target angle.

From Figure 5 to Figure 7, it can be seen that the adaptive parameters are within the set range. The
parameter curve of the high-angle motion of the coordinator is shaken than the parameter curve of the
low-angle motion, and the overall impact on the system is more obvious at high angle. It can be seen
from Fig. 8 that the DOB can quickly respond to changes in the speed of the system in a short time to
changes in disturbance torque and system parameters, and compensate for external disturbances, so
that the coordinator reduces severe chattering and improves control accuracy. When the target angle is
30 ° and 45 °, the perturbation torque of the perturbation observer is relatively small, but at 70 °, the
system impact is large, and the perturbation torque generated is significantly increased.

5. Conclusion

In this paper, an adaptive sliding mode control strategy based on DOB is applied to control research of
artillery coordinator, and it is applied to hydraulic servo system. The AMEsim and MATLAB
electro-hydraulic joint simulations show that the adaptive algorithm can well estimate the parameter
values and guarantee fluctuations within the boundary. The disturbance observer can feed forward
compensate the system, which greatly reduces the unmodeled disturbance pairs and unknown
parameters. It affects the system control accuracy, and greatly reduces the chattering phenomenon
existing in traditional sliding mode control, which makes the positioning process more stable and
improves the positioning accuracy.

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