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Improvement on performance of electro-hydraulic central position control system by adaptive reaching law sliding mode method

***Abstract**. The switching function and its change are used as input, the index reaching law parameters that represent chattering is used as output, design the switch function sliding mode control method based on fuzzy adaptive reaching index law. Applying for electro-hydraulic central position control system of single roller for a large silicon steel company, and co-simulation between the physical model of the hydraulic system and controller model is implemented, analyze the response characteristics, tracking accuracy and control chattering of the system. The research results show that the strategy has fast response, high control precision and smaller chattering.*

***Streszczenie.** Opisano metodę sterowania układem elektro-hydraulicznym w napędzie taśmowym stosowanym w przedsiębiorstwie produkującym stal krzemową. Na wejściu analizuję się funkcję przełączania – na wyjściu analizuje się drgania. Do sterowania wykorzystuje się metody logiki rozmytej. (**Poprawa właściwości systemu sterowania układem elektro-hydraulicznym przez zastosowanie adaptacyjnej metody ślizgowej**)*

Keywords: Reaching law, Arrival speed, Electro-hydraulic system, Chattering
Słowa kluczowe: system elektro-hydrauliczny, sterowanie

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Introduction

Electro-hydraulic position servo system are with features of essentially nonlinear and parametric uncertainties, which affect the control performance improvement, as a nonlinear variable structure control method through structural adjustments and changes can be effectively applied to electro-hydraulic servo system [1-2].

Sliding mode variable structure control systems "robust" is stronger than the average conventional continuous control system. But for a real variable structure systems, control is limited, the system inertia switch has lag of time and space, detect errors and discrete systems form the "quasi-sliding", etc., that will result in "chattering." Many scholars around the research carried out to eliminate buffeting, but sliding mode variable structure of the system parameter perturbation and external disturbance invariance produce high-frequency buffeting , due to the high frequency chattering is infinitely fast in the theoretical analysis, but it has no real actuator can be realized in practice. Therefore, only to weaken buffeting, not completely eliminate, eliminates buffeting also eliminates the sliding mode variable structure system anti-disturbance capability. There are many researches on new slide mode control method, which include nerve slide control, adaptive fuzzy slide mode control, slide mode observer control, multi-model switching slide mode control, higher order terminal slide mode control, etc.,[3-7].

Reaching law strategy is method of sliding mode control suitable for engineering applications, not only the location of the system from switching surface can be analyzed, and also can be designed for approaching the process, thus reaching law sliding band size can be calculated with a switch to strike, has the benefits of sliding mode control law is easy to realize. The traditional switching surface reaching law outside the normal motion segment and switching surface in sliding sections can be designed separately, but the entire transition process quality problem can not be solved in one time, often using two stages engineering methods to ensure their achieve. Also the technical bottleneck is either too large approaching speed or too large arrival speed will result in a strong buffeting the system, resulting in the deterioration of control performance [8-12].

During solving the problems, there are a number of ways, but the problem exists that either reduce the system robustness at the same time weaken the buffeting, or policy is too complex only for the computer simulation that can not be putted into practical engineering applications. Therefore, the design an advanced sliding mode variable structure strategy has very real significance that meets the real-time, robustness requirements, and effectively inhibits the buffeting.

System description

Define deviation e=r-y, r – position given signal, y – output location signal.

Define e_1=r-y, $e_2 = \dot{e} = \dot{r} - \dot{y}$, $e_3 = \ddot{e} = \ddot{r} - \ddot{y}$, the description of electro-hydraulic position servo system state space is as follows:

$$\begin{cases} \dfrac{de_1}{dt} = e_2 \\ \dfrac{de_2}{dt} = e_3 \\ \dfrac{de_3}{dt} = -a_2 e_3 - a_1 e_2 - a_0 e_1 - b_0 u(t) + F(t) \end{cases} \tag{1}$$

where: $F(t)$ – generalized disturbance quantity, its math description is as follows:

$$F(t) = \frac{d^3 r}{dt^3} + a_2 \frac{d^2 r}{dt^2} + a_1 \frac{dr}{dt} + a_0 r \tag{2}$$

where: $a_0 = \dfrac{4KK_{ce}\beta_e}{m_t V_t}$, $a_1 = L + \dfrac{4B_p K_{ce}\beta_e}{m_t V_t} + \dfrac{K}{m_t}$, $L = \dfrac{4\beta_e A_p^2}{m_t V_t}$, , $a_2 = \dfrac{4K_{ce}\beta_e}{V_t} + \dfrac{B_p}{m_t}$, $b_0 = \dfrac{4K_v K_{sv} K_Q \beta_e A_p}{m_t V_t}$, $x_v = K_v K_{sv} u$.

K_Q – flow gain, K_{Ce} – flow pressure coefficient, x_v – spool travel, A_p – area of cylinder piston, V_t – total compressed area of hydraulic cylinder, β_e – active bulk modulus, m_t – total mass of piston and load converted to piston, B_p – viscous damping coefficient of piston and load, K is load spring rate, K_v is controller gain, K_{sv} is serving valve gain; u is control voltage signal.

Design of fuzzy adaptive reaching law slide mode controller for electro-hydraulic central position control

Electro-hydraulic central position control system

In the strip unit, although it is designed with a number of measures for the strip central position control, but the deviation is still unavoidable. Such as rewinding missing, units in rolls deviation, vibration, roll system not parallel and non-level degree, eccentric or taper roller, strip thickness uneven, wave-shaped, lateral bending, hardness, surface roughness, tension changes and other reasons. Because the strip is not affixed evenly and symmetrically around the roller, various asymmetry factors cause lateral force that perpendicular to the forward direction.

Fuzzy adaptive reaching law slide mode controller

This index reaching law math description is as follows:

(3) $$\dot{s} = -\varepsilon sign(s) - ks, \quad \varepsilon > 0, \quad k > 0$$

At the same time meet the condition of generalized slide mode.

When $s(x)>0$, $\dot{s} = -\varepsilon - ks$, $s(t) = -\frac{\varepsilon}{k} + (s_0 + \frac{\varepsilon}{k})e^{-kt}$

When $s(x)<0$, $\dot{s} = \varepsilon - ks$, $s(t) = \frac{\varepsilon}{k} + (s_0 - \frac{\varepsilon}{k})e^{-kt}$

where: s_0 – the original value of switching function $s(x)$, k – reaching speed index, ε – arriving speed index, t is time.

(4) $$u = \begin{cases} u^+(x) & s(x) > 0 \\ u^-(x) & s(x) < 0 \end{cases}$$

Take switching function as $s=c_1e_1+c_2e_2+e_3$, so

Under the generalized slide mode condition $s(ds/dt)<0$ is satisfied, then

(5) $$\begin{cases} u^-(x) < [-a_0e_1 + (c_1 - a_1)e_2 + (c_2 - a_2)e_3 + F(t)]b_0^{-1} \\ u^+(x) > [-a_0e_1 + (c_1 - a_1)e_2 + (c_2 - a_2)e_3 + F(t)]b_0^{-1} \\ F(t) = \dddot{r} + a_2\ddot{r} + a_1\dot{r} + a_0r \end{cases}$$

Function switching slide mode control makes no rule for reaching procedure, so it has effect on its movement characteristic. Adopt index reaching law control based on the strategy has observable function for improving the dynamic quality of normal motion segment.

Letbe $\dot{s} = -\varepsilon sign(s) - ks(\varepsilon, k > 0)$, then

(6) $$\begin{aligned} \dot{s} &= -a_0e_1 + (c_1 - a_1)e_2 + (c_2 - a_2)e_3 + F(t) - b_0u(t) \\ &= -\varepsilon sign(s) - ks \end{aligned}$$

So:

(7) $$\begin{aligned} u(t) &= [-a_0e_1 + (c_1 - a_1)e_2 + (c_2 - a_2)e_3 + F(t) + \varepsilon sign(s) \\ &+ ks]b_0^{-1} = [(kc_1 - a_0)e_1 + (c_1 + kc_2 - a_1)e_2 + (c_2 - a_2 + k)e_3 \\ &+ F(t) + \varepsilon sign(s)]b_0^{-1} \end{aligned}$$

Fuzzy adaptive index reaching law slide mode controller

Electro-hydraulic servo control system has been widely used in central position control system,its parameter is shown in table.1.

Table.1 Model parameter

hydraulic cylinder inner diameter D	0.08 m
piston rod diameter d	0.063 m
hydraulic cylinder effective area A_P	1.53×10^{-3} m^2
piston displacement h	0～0.4 m
total mass m_t	250 kg
hydraulic cylinder two antrum volume V_t	0.107×10^{-3} m^3
viscous damping coefficient B_p	8.8×10^{-5} N·s/m
active volume elastic modulus β_e	7×10^{8} N/ m^2
servo valve rated flow Q_L	40 L/min
total flow pressure coefficient K_{ce}	4.35×10^{-12} m^3/s·pa
servo valv rated current I	300 mA (dead zone 10 mA)

Two input single output two dimensions fuzzy controller is designed, with switching function $s(x)$ and its derivative $\dot{s}(x)$ as input variable, arriving speed index which reflect system chattering index as output, and fasten value of k. Where $\varepsilon = \left| f(s(x), \dot{s}(x)) \right|$. Define 5 fuzzy sets to switching functions $s(x)$ and $\dot{s}(x)$, they are positive big (PB), positive small (PS), zero (ZR), negative small (NS),negative big (NB). ε defines 7 fuzzy sets, they are positive big (PB), positive middle (PM),positive small (PS), zero (ZR), negative small (NS), negative middle (NM), negative big (NB). Then

Taking the system parameter, according to electro-hydraulic serving system parameter, calculating by quadratic form best method, we get: c_1= ω_n^2 =24336， c_2= $2\delta\omega_n$=221 (ω_n – system fixed frequency, δ – damping ratio). The parameters experience value adopted by simulation, the value range of switching function is [-50000～+50000], the value range of switching function derivative is [-10000～+10000], the value range of index reaching law parameter ε is [-100～+100], finally quantificat to the fuzzy universe as follows:

(8) $$\begin{cases} s = \{-5,-4,-3,-2,-1,0,+1,+2,+3,+4,+5\} \\ \dot{s} = \{-5,-4,-3,-2,-1,0,+1,+2,+3,+4,+5\} \\ \varepsilon = \{-4,-3,-2,-1,0,+1,+2,+3,+4\} \end{cases}$$

The left side uses Z shape membership function and the right side uses S shape membership function to describe a complete fuzzy conception. The others choose triangle membership function to describe the intermediate state. Table.2 is the fuzzy query table.

Table.2 Fuzzy query table

$s(x)$ \ ε \ $\dot{s}(x)$	NB	NS	ZR	PS	PB
NB	NB	NM	NM	PS	ZR
NS	NM	NS	NS	ZR	PM
ZR	NS	NS	ZR	PS	PS
PS	PM	ZR	PS	PM	PM
PB	ZR	PM	PM	PM	PB

Co-simulation and characteristic comparison

The control system is designed to track the square wave position in the engineering, comparing the feedback signal and the setting signal, sending the signal of position, speed and acceleration to controller function S as the input to control the reaching law slide mode. Input signal through the amplitude limiting link to restrict the maximum output current of serving amplifier.

This paper primarily researches the characteristic of square wave tracking under variable control methods. The given square wave amplitude is 10 mm. According to the value c_1, c_2 and the reaching speed index k=0.01 adopted by simulation result, the nonlinearity of serving value, the uncertainty of electro-hydraulic serving system parameter and the saturability are realized by AMEsim model, choosing the designed control tragedy parameter to co-simulate.

Reaching law parameter type Ⅰ: $\varepsilon = 50$. Reaching law parameter type □: ε = 10. Reaching law parameter type □: fuzzy adaptive reaching law. Reaching law parameter □, □, Ⅲ system characteristics are shown in fig.1, fig.2 and fig.3. That shows the step response characteristic.

It can be known from fig.1 that when adopting parameter type Ⅰ, system respond time is 0.13 s, steady state error is 1.1 mm, moving point arrives the switching interface with high speed, system dynamic response is fast, but control variable switches frequently which causes chattering obviously, applying to realistic system can cause noise and chattering.

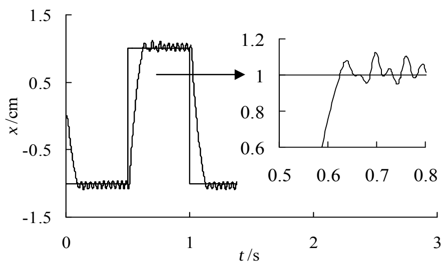

Fig.1 The square wave respond of parameters type Ⅰ

It can be known from fig.2 that when taking parameter type □, system response time is 0.18, steady state error is 1.0mm, at this time, chattering amplitude is at the range of serving valve dead zone, so the control variable has no chattering, reaching slowly, adjusting slowly, the control variable chattering disappears, control precision has no obvious change comparing to parameter type □. So the chosen reaching speed index has big effect on entire control system performance, abandoning the speed while inhibiting chattering to ensure precision.

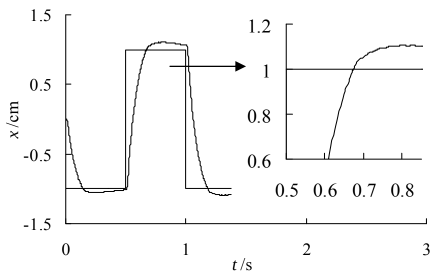

Fig.2 The square wave respond of parameters type□

It can be known from fig.3 that when taking parameter type Ⅲ, using the distance of state point and switching interface and moving speed as the reference. The speed of arriving the switching interface according to the fuzzy adaptive index reaching law control is ε, system respond time is 0.1s, steady state error is 0.05 mm, at this time, the chattering effect is slightly beyond serving value dead zone. In the realistic application, the function is similar to the chattering signal of overcoming the dead zone effect, its noise and chattering effect is beyond the engineering allowable range.

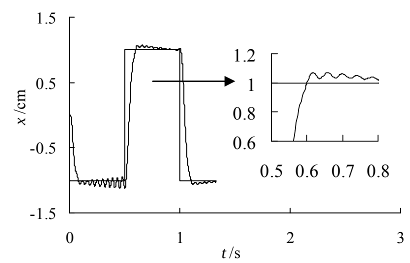

Fig.3 The square wave respond of parameters type □

Conclusion

(1) Fixed reaching speed index is adopt, taking three type of arriving speed, system respond time is 0.13s, 0.18s, 0.1s respectively. Steady state error is 1.1mm, 1.0mm, 0.05 mm respectively. So when *k* value is fixed, adopt the large ε can accelerate system respond, but at the same time, it can cause big chattering and steady state error, adopt the small ε can slow the system respond. Adopt adaptive adjusting ε can adjust both respond time and steady state error, control the amplitude of chattering near the slide mode interface is similar to the dithering to obtain better control effect.

(2) AMEsim of co-simulation can comprehensive consideration of the electro-hydraulic system nonlinear and uncertainty of various parameter, it is closer than the practical system. The result of theoretical analysis is fit for the co-simulation, the simulation result can offer basis for the parameter choosing and effect evaluation of practical system.

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