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A SERME Control in the Hydraulic or Electric Type Drive Application

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Abstract

One relay control implementation to the servo control systepm is contrived mainly for the high power electric or electro hydraulic type drive system. Proposed SERME control is relay emulated software scheme accounting a relay producing maximum torque in both direction in the insufficient bandwidth control system. Possibility is proposed mathematically prior to emperical work out.

1. Introduction

This is a follow-up work to "The electric and electro-hydraulic type high power drive" (Ahn 1995). Some of practically encounted probllems during high power drive system development either by electric or by hydraulic measure are full utilization of power, minimum time control, consistent precision control, etc. Relay control has been applied diversely, and particularly used in case of insufficient bandwidth for precision position control in the past. But not much has been done in the servo control system with relay implementation. Proposed SERME (sign error multiplys root of magnitute of error) method (Landers 1983) is aiming to control the high power drive system especially under consideration for military purpose. Experimental work is on the way and ensued later. Biernson developed a equation for a gain decision in the position servo control loop. Case studies have been done for the motor control and electro-hydraulic valve control of the same parameters given in (Ahn 1984). SERME is mathematically developed and gain substitue is shown instead of a simplified position and velocity feedback system together with Biernson's equation connection. Discussion is given with regard to the SERME effectiveness on the state of the art technology.

2. Satuation (Biernson)

When slewing it is reasonable to argue that for minimum time control the system must be saturated throughout. The velocity of the load would then be like in Fig.1.

$$\theta_{max} = \frac{\theta_{max}}{t_1}, \qquad t_1 = \frac{\theta_{max}}{\theta_{max}} \qquad \text{------- (1)}$$

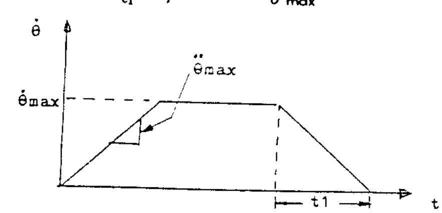

Fig.1. Minimum Time Control Profile

A simple double integration yields the error

$$e_1 = \frac{1}{2}\theta_{max}\, t_1^2 \qquad \text{-------- (2)}$$

Consider now the following simplified position servo as in Fig.2.

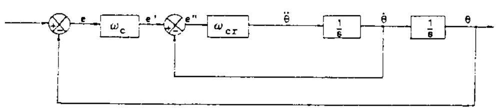

Fig.2. Simplified Conceptual Sero-loop

$$\frac{\theta}{e''} = \frac{\omega_{cr}}{S} \qquad \text{—— (3)}$$

and

$$\frac{\theta}{e'} = \frac{\omega_{cr}/S}{1+\omega_{cr}/S} = \frac{\omega_{cr}}{S+\omega_{cr}} \qquad \text{—— (4)}$$

$$\frac{\theta}{e} = \frac{\omega_{cr}\,\omega_c}{S(S+\omega_{cr})} \simeq \frac{\omega_c}{S} \qquad \text{—— (5)}$$

if ω_{cr} is large

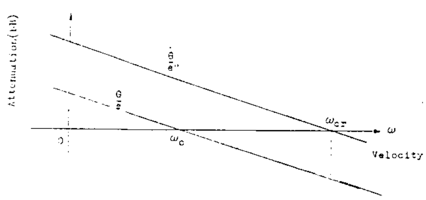

Fig.3. Attenuation Diagram

$$\theta = \omega_{cr} \quad e'' = \omega_{cr}(e' - \theta) = \omega_{cr}(\omega_c e - \theta) \qquad \text{---- (6)}$$

Therefore,

θ change sign when $e = \theta/\omega_c$ If ω_{cr} is large

And therefore,

$$\frac{\theta_{max}}{\omega_c} = \frac{1}{2}\frac{\theta^2_{max}}{\theta_{max}} \text{ or } \omega_c = \frac{2\theta_{max}}{\theta_{max}} \qquad \text{— (7)}$$

Acceleration limits result from current or pressure limits while velocity limits result from voltage or flow limits. Then it is easy enough to calculate the required gain ω_c.

<Example>

Futher calculation shows that $\omega_{cr} > \omega_c$ is sufficient and for this to be true

$$\frac{V_{sat}}{I_{sat}} > 4\Omega \quad \text{or} \quad \frac{Q_{sat}}{P_{sat}} > 4L \qquad \text{———— (8)}$$

The resistance associated with the armature of an electric motor including its power amplifier output stage is between 1.0Ω and 10Ω.

If $V_{sat} = \pm 50V$, then

$$I_{sat} < \frac{V_{sat}}{4R} = \frac{50}{1} = 50A \qquad \text{———— (9)}$$

This si not necessarily so, 100A might be a better estimate of I_{sat}. In the hydraulic case, a two stage electro-hydraulic valve may have the following parameters (at 1000 lbf/in^2)

Table1. Valve Parameters

Flow Rate $m^3/s(in^3/s)$	Freq.Resp. (-3db) Hz	Phase/Lag (40/90) Hz	Internal Leakage in^3/s	Compressed Oil Volume in^3	Weight l b
80×10^{-6}(5)	50	50.125	0.6	0.08	2.75
320×10^{-6} (20)	60	50.125	0.8	0.09	2.75
500×10^{-6} (30)	60	50.125	1.1	0.1	2.75
640×10^{-6} (40)	50	50.125	1.1	0.17	2.75
10^{-3} (60)	50	40.90	1.8	0.17	2.75
1.6×10^{-3} (100)	45	25.50	4	0.52	15
2.6×10^{-3} (160)	20	15.40	6	1.36	25

$$P = 1000\ lb_f/in^2 = 6.895\times10^6\ N/m^2$$

$$\frac{Q}{P} = \frac{80\times10^{-6}}{6.895\times10^6} \sim \frac{2.6\times10^{-3}}{6.895\times10^6}$$

$$= 11.6\times10^{-12} \sim 377.1\times10^6 \left(\frac{m^3}{S}, \frac{m^2}{N}\right) \qquad \text{—— (10)}$$

For motor cases, consler now motor data.

Table2. Motor Parameters

d_m in^3/rev	Leakage in^3min^{-1}/psi	J_m $inlb/sec^2$	Compressed Oil Volume in^3	Reference Data
1	0.035	0.002	1	Motor Displace-ment 2.5×10^{-6} to 20×10^{-6} m^3/rad
2.2	0.04	0.006	1.5	Compressed Vol 15×10^{-6} to 8.4×10^{-6} m^3
5	0.08	0.015	3.2	
7.6	0.1	0.026	5.1	Motor Inertia 0.0002 - 0.0026 Kgm^2

Losses are then $0.035 \sim 0.1\ in^3min^{-1}/psi$ or

$$0.01386\times10^{-10} \sim 0.0396\times10^{-10}\ m^5/N\ sec \qquad \text{— (11)}$$

Valve losses $0.036 \sim 0.36$ $in^3 min^{-1}/psi$ or

$1.4256 \times 10^{-12} \sim 1.4256 \times 10^{-11}$ m^5/N sec — (12)

Total losses are then about 2.5×10^{-12} to

18.2×10^{-12} m^5/N sec ------ (13)

Therefore,

11.6×10^{-12} to 377.1×10^{-12} m^5/N sec is usually

$> 4 \times 2.5 \times 10^{-12}$ to $4 \times 18.2 \times 10^{-12} m^5/N sec$ – (14)

But in neither case is this criterion necessarily met.

3. SERME

If we have insufficient bandwidth in the inner loop, then, a solution considered in the past involves a relay which produces maximum torque in either direction. The equation of motion under torque limited conditions are

$$S^2 \theta_o = \frac{T_{max}}{J} \qquad (15)$$

$$S\theta_o = \frac{T_{max}}{J} t + C_1 \qquad (16)$$

$$\theta_o = \frac{T_{max}}{J} \frac{t^2}{2} + C_1 t + C_2 \qquad (17)$$

Where C_1 is the velocity with which the system enters the torque limited region.

Consider now the relay system. Let the voltage on the relay operating coil for error be K_1 ; let the voltage on the relay operating coil for unit C/P shaft velocity be K_2. The net voltage on the relay operating coil is then

$$K_1 e - K_2 S\theta_o \qquad (18)$$

The torque is then given by

$$T = -T_{max} Sgn(K_1 e - K_2 S\theta_o)$$

$$= +T_{max} Sgn(K_1\theta_o + K_2 S\theta_o) \qquad (19)$$

* Positive error must produce negative torque

Where $e = -\theta_o$, note θ_i assumed zero.

The torque change over condition is then

$$K_1\theta_o = -K_2 S\theta_o \text{ or } \theta_o = -\frac{K_2}{K_1} S\theta_o \qquad (20)$$

A case of particular interest is that (in which the magnitude of the initial displacement is set so that torque is reversed when the O/P shaft has moved exactly half way) we go from maximum acceleration to maximum deceleration just at the correct time to bring the load to a stop just where we want it.

Let this value be θ_d.

Then, $\theta_o = \frac{T_{max}}{J}\frac{t^2}{2} - \theta_d$.

Where $C_2 = -\theta_d$, and $C_1 = 0$ ——— (21)

When,

$$\theta_o = \frac{\theta_d}{2}, \text{ we have } -\frac{\theta_d}{2} = \frac{T_{max}}{J}\frac{t^2}{2} - \theta_d \qquad (22)$$

Therefore,

$$\theta_d = -\frac{T_{max}}{J} t^2 \quad or \quad t = \sqrt{\frac{\theta_d J}{T_{max}}} \qquad (23)$$

And therefore,

$$S\theta_o = -\frac{T_{max}}{J} t = \frac{T_{max}}{J}\sqrt{\frac{\theta_d J}{T_{max}}} = \sqrt{\frac{\theta_d T_{max}}{J}} \qquad (24)$$

But, $\theta_o = -\frac{K_2}{K_1} S\theta_o = -\frac{K_2}{K_1}\sqrt{\frac{\theta_d T_{max}}{J}}$ —— (25)

Therefore,

$$-\frac{\theta_d}{2} = -\frac{K_2}{K_1}\sqrt{\frac{\theta_d T_{max}}{J}} \qquad (26)$$

And therefore,

$$\frac{\theta_o^2}{4} = \left(\frac{K_2}{K_1}\right)^2 \theta_d \frac{T_{max}}{J} \qquad (27)$$

Lastly,

$$\theta_d = \frac{4(K_2)^2 T_{max}}{(K_1)^2 J} \qquad (28)$$

For a particular value of θ_d, we can obviously choose K_1 and K_2 so that this condition is satisfied. But the required values of K_1 and K_2 will vary for different disturbances. We would like this condition, which is the condition for constant response to disturbance, to be satisfied for any disturbance amplitude. This can be done if the value of the velocity feedback gain K_2 is varied automatically so that the relay changes over exactly at

$$e = -\frac{\theta_d}{2} \forall \theta_i \qquad (29)$$

Now

$S\theta_o = \frac{\sqrt{\theta_d T_{max}}}{J}$ and $\theta_d = 4\frac{K_2^2}{K_1^2}\frac{T_{max}}{J}$ - (30)

Eliminating θ_d, we have

$$(S\theta_o)^2 \frac{J}{T_{max}} = 4\frac{K_2^2}{K_1^2}\frac{T_{max}}{J} \qquad (31)$$

Therefore,

$$K_2{}^2 = \frac{K_1{}^2}{4}\frac{J_2}{T_{max}}(S\theta_o)^2 \qquad \text{—— (32)}$$

And,

$$K_2 = +\frac{K_1 J}{2T_{max}}\lceil \omega_o \rceil \quad when \quad \omega_o = S\theta_o \qquad \text{— (33)}$$

K_2 must remain positive so that the velocity feedback remains negative. Therefore, we have taken the postive root. We previously had

$$T = -T_{max}\, sgn(K_1 e - K_2 s\theta_o) \qquad \text{— (34)}$$

Therefore, $T = -T_{max}\, sgn(K_1 e - K_2 s\omega_o)$

$$= -T_{max}\, sgn\left(K_1 e - \frac{K_1 J}{2T_{max}}\lceil \omega_o \rceil \omega_o\right) \qquad \text{—— (35)}$$

(This is exactly the formula in the Zanker paper)

The equation of the change over line is then

$$e = \frac{J}{2T_{max}}\lceil \omega_o \rceil \omega_o \quad or$$

$$\theta_o = -\frac{J}{2T_{max}}\lceil \omega_o \rceil \omega_o \qquad \text{—— (36)}$$

In the days when V stood for velocity this was called V mod V for obvious reason. It was also regarded as difficult to produce a velocity feedback gain of $J/(2\,T_{max})\lceil\omega_o$. So the square root of each of the bracketed quantities was considered, i.e.

$$\sqrt{K_1 e} - \sqrt{\frac{K_1 J}{2T_{max}}}\,\omega_o \qquad \text{—— (37)}$$

This quantity changes sign whenever the original one does. We say then

$$T = -T_{max}\, sgn\left(sgn(e)\sqrt{\lceil e \rceil} - \omega_o\sqrt{\frac{J}{2T_{max}}}\right) \qquad \text{— (38)}$$

Where again we have carried through the sign of the variable when possessing the square root. This system is called SERME - Sign Error X Root of Magnitude of Error

For change over

$$sgn(e)\sqrt{\lceil e \rceil} = \sqrt{\frac{J}{2T_{max}}}$$

$$\omega_o = sgn(e)\sqrt{\lceil e \rceil} = \sqrt{\frac{2T_{max}}{J}} \qquad \text{—— (39)}$$

$$\omega_o^2 = \lceil e \rceil \frac{2T_{max}}{J} \quad \text{: see for V mod V} \qquad \text{— (40)}$$

4. Connection between Biemson and SERME

Fig.4. Simplified Position and Velocity Feedback System

Consider $\theta = K_v(K_d e - \theta)$. We switch to maximum deceleration when $K_d e = \theta$. Biemson says that $K_d = 2a/\theta$ or $e = \theta^2/2a$. This is the switching line. But this is the switching line for SERME, and to obtain SERME we say

$$\theta = \sqrt{2ae} \quad or \quad \theta = \sqrt{\frac{2T_{max}}{J}}\, sgn(e)\sqrt{\lceil e \rceil}.$$

We then have

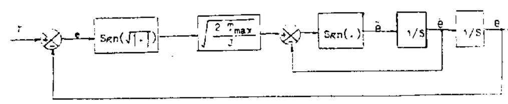

Fig.5. Servo Control System with Relay Implementation

5. Objections to SERME

This method evolved when electrical systems didn't use control of field current of electric servo motors : i.e. there was no 'back emf' loop. There was therefore direct control of the motor torque.

$$T = \frac{P\Phi Z}{2\pi a} I_a = \frac{PZ}{2\pi a} K_F I_F I_a = K' I_F \qquad \text{—— (41)}$$

Electronic devices of those days(tubes) could not deal with armature currents.

But armature controlled electric motor, and flow controlled hydraulic motors are effectively velocity controlled devices. Maximum voltage or flow will not necessarily produce maximum torque because speed build up will tend to reduce the torque. It might be argued that if we use significant torque feedback then on input signal will control torque rather than velocity. From a linear point of view this is certainly so.

Consider the electrical case using armature current feedback(which amounts to the same thing).

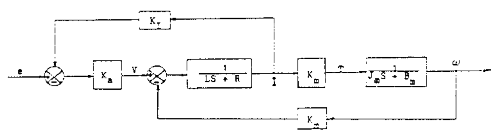

Fig.6. Current Feedback Servo Control System

For simplicity, the time constant of the power amplifier is ignored

$$T = J_m \frac{d\omega}{dt} + B_m \omega = K_m I \qquad (42)$$

and $$V = L\frac{dI}{dt} + RI + K_m \omega \qquad (43)$$

$$V = K_a(e - K_I I) \qquad (44)$$

Require the transfer function for T/e

Therefore,

$$K_a(e - K_I I) = L\frac{dI}{dt} + RI + K_m \omega \qquad (45)$$

And,

$$K_m \omega = K_a e - (K_a K_I + LS + R) I \qquad (46)$$

Also,

$$(J_m\ S + B_m)\omega = K_m I \quad or \quad \omega = K_m \frac{I}{J_m S + B_m} \qquad (47)$$

Therefore,

$$\frac{K_m^2 I}{J_m S + B_m} = K_a e - (K_a K_I + LS + R) I \qquad (48)$$

And

$$[K_m^2 + (K_a K_I + LS + R)(J_m S + B_m)] I = (J_m S + B_m) K_a e \qquad (49)$$

Steady state gives

$$(K_m^2 + K_a K_I B_m + R B_m) I = B_m K_a e \qquad (50)$$

Therefore,

$$\frac{I}{e} = \frac{B_m K_a}{K_m^2 + (K_a K_I + R) B_m} \qquad (51)$$

Let $K_a K_I$ be large

$$\frac{I}{e} \simeq \frac{1}{K_I} \quad or \quad \frac{T}{e} \simeq \frac{K_m}{K_I} \qquad (52)$$

Therefore, e controls T.

But this is based on linearity. Suppose the SERME system switches e hard over one way. Then as ω rises, $K_m \omega$ will begin to cause I or T to reduce. This is the original objection to SERME. However, it might be argued that the K_I loop tends to counter this. Certainly V will tend to rise if I drops and e remains constant (as it will). But if V was also saturated it could not rise further. Nevertheless this is a way to produce a SERME control in either the flow controlled hydraulic or armature controlled electric system.

6. Discussion

A SERME control is discussed especially in relation to the flow controlled hydraulic or armature controlled electric system. In highly demaned trend of maximum power utilization, this control would be another substitue for the control sheme though not very well proved through the elabrate experiment. Further analytical and emplrical work result will be presented including sallent features resulted from hardware advancement. None the less this control, hopely and surely, is one way of solution.

References

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