APPLICATION OF SLIDING CONTROL IN DC ELECTRIC DRIVES WORKING WITH LOAD THROUGH FLEXIBLE JOINTS

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ABSTRACT

Electric drive systems are widely used in most sectors of the national economy. The basic task of the system is to convert electrical energy into mechanical energy and control that conversion process in working machines, especially in modern automatic production lines. Automatic electric drive systems play an important role in improving productivity and product quality. The control theory of a system with a variable structure is a difficult theory, based on the theory of differential equations with a discontinuous right-hand side. The sliding control method needs to be studied in more detail so that it can be applied to synthesize controllers for non-linear, non-stationary systems, under the motion of unknown components, disturbances...

Keywords: Automatic electric drive; automatic control theory; DC electric motor; slide control.

1. INTRODUCTION

The theory of analysis and synthesis of automatic electric drive systems needs to be researched to meet new technological requirements with increasing levels of automation. The mathematical model that describes the motion of the control object taking into account non-ideal components is often nonlinear and time-dependent, and has unknown impact components (impact disturbances). to the system) [3,8,11,12]. When considering that the joints between the motor shaft and the actuator rotation shaft are not absolutely rigid, and there are friction components present, the mathematical description of the system will become much more complicated and Then, synthesizing control using classic theoretical tools will be difficult and even impossible to solve. Thus, when calculating and designing this electromechanical system, it is necessary to have modern design tools such as: Modern control theory, calculation elements to create digital control laws (DSP, FPGA...) [5,6 ,7]. The control theory of a system with a changing structure, especially the sliding mode that appears in the control system when constructing intermittent feedback, was developed in the 50s of the last century until now and still remains intact. news and has applications in synthesizing robust control laws against the effects of disturbances and unknown components.[8,9,10]

2. ANALYSIS

2.1. Equation of motion of the system taking into account friction and elasticity

Frictional force always tends to oppose motion (for dynamic friction) or motion (for static friction) between two surfaces in contact. The friction coefficient is an empirical quantity; it is determined during experimentation, not from calculation. Rough surfaces are capable of producing higher values for the coefficient of friction. Most dry materials combined give a coefficient of friction between 0.3 and 0.6. Values outside this range are rare, but Teflon can have a coefficient of friction as low as 0.04. The valuable friction coefficient appears not only in the case of levitation thanks to a magnetic field. Rubber on other contact surfaces usually has a coefficient of friction between 1.0 and 2.

- Modeling the DC electric drive circuit through flexible coupling:

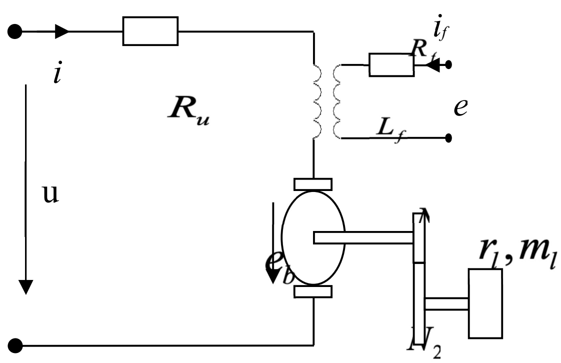


Fig. 1. *Diagram of transmission*

In the above drive diagram, the actuator is a DC motor, with the following variables and parameters:

u(t): armature voltage

R_u: armature resistance

L_u: armature inductance

i_u: armature current

e_b: armature electromotive force

e_f: inductor voltage

R_f: sensing resistance

L_f: inductance of the sensing part

i_f: inductor current

N_1, N_2: gearbox gears

r_l: radius of the load

m_l: load volume

θ: rotation angle of the motor rotor

K_b: armature electromotive force coefficient

- Mechanical part motion equation:

In reality, the speed changer consists of many gears linked together. But here we only consider the two terminal gears in the speed changer. Assume that all types of friction in the system are negligible and can be ignored.

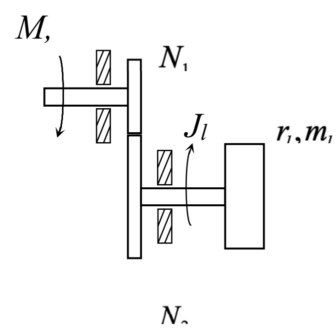


Fig. 2. *Mechanical transmission system diagram*

- Kinetic equation of the executive motor:

Mathematical model of the drive system using state variables.

Set state variable:

$x_1 = \theta$ rotation

$x_2 = \dot{\theta}$ angular velocity

$x_3 = i_u$ armature current

We get the equation in state space $X = [x_1\, x_2\, x_3]^T$

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = \frac{K_i}{J_{eq}} x_3$$

$$\dot{x}_3 = -\frac{K_b}{L_u} x_2 - \frac{R_u}{L_u} x_3 + \frac{1}{L_u} u \qquad (1)$$

Write in matrix form: $\dot{X} = AX + Bu$

Output measurement assumes rotation angle

We have the output measurement equation: $Y = CX$ $C = [1 \quad 0 \quad 0]$

Expanded, we can consider the electromechanical system as a third-order nonlinear model

$$\dot{x}_1 = f_1(x_1) + x_2$$

$$\dot{x}_2 = f_2(x_1, x_2) + x_3 \; \dot{x}_3 = f_3(x_1, x_2, x_3) + bu$$

$$y = x_1$$

- Equation of motion of the system when taking into account friction and elasticity

The resisting moment can be constructed as:

$$M_c = (M_{c0} sign\, \varphi_2 + M_{c1} \frac{d\varphi_2}{dt}) \qquad (2)$$

M_{c0} Characteristic coefficient for static friction, depending on the direction of rotation angle

M_{c1} Characteristic coefficient for dynamic friction, proportional to the angular velocity of rotation.

Set state variables:

- Rotation angle on the actuator: $x_1 = \varphi_2$

- Angular speed: $x_2 = \frac{d\varphi_2}{dt} = \omega_2$

- Rotation angle at the top of the motor shaft: $x_3 = \varphi_1$,

- Angular speed on motor shaft end: $x_4 = \frac{d\varphi_1}{dt} = \omega_1$

- Armature current of the executive motor: $x_5 = i_u$

We have the following equations:

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = \frac{1}{J_2} C(x_3 - x_1) - \frac{1}{J_2}(M_{c0} sign x_1 + M_{c1} x_2)$$

$$\dot{x}_3 = x_4$$

$$\dot{x}_4 = \frac{K_i}{J_2} x_5 - \frac{1}{J_2} C(x_3 - x_1) \qquad (3)$$

$$\dot{x}_5 = -\frac{K_b}{L_u} x_4 - \frac{R_u}{L_u} x_5 + \frac{1}{L_u} u$$

Output measurement equation: $y = x_1$

Thus, when taking into account the elastic connection between the motor shaft and the working mechanism, the model size will increase (5th order system).

2.2. Control of DC electric drive system based on sliding control

2.2.1. Slider control

- Sliding control was first studied by Emelyanov and colleagues (1957) and developed by Utkin (1974) [15], [16], and a series of other Western European authors Slotine J.J.E [6].. .The mathematical basis of the research is based on the theory of differential equations with discontinuous right-hand side by author Philipov. The content of the method includes two steps. First of all, choose a sliding surface that ensures the trajectory error always approaches 0. Then, choose an appropriate control law to bring the state of the closed system moving to the sliding surface and be stable on the sliding surface. This method has high control accuracy and is stable against load disturbances and changes in parameters of the control object.

- Slip phenomenon: Consider the system shown in Figure 3, [2] with the two-position link being the only nonlinear link, the remaining links are all linear and described by the transfer function:

$R(s) = \frac{1}{s}$ is the linear part of the nonlinear controller

$S(s) = \frac{1}{Ts}$ is a model of a linear object

$M(s) = k$ is a model of a feedback signal measuring device, assumed to be linear and inertialess.

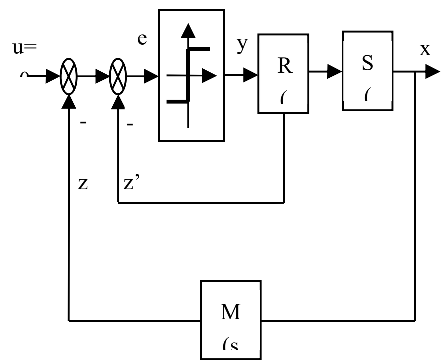


Fig. 3. *System with two-position nonlinear coupling and no excitation*

The transfer function of the nonlinear stages, we have:

$$\frac{d^2x}{dt^2} = \begin{cases} \frac{1}{T} \text{ nếu} & kx + T\frac{dx}{dt} < 0 \\ -\frac{1}{T} \text{ nếu} & kx + T\frac{dx}{dt} > 0 \end{cases} \quad (4)$$

From system (4), we can determine that the phase plane will be the plane with two coordinate axes x and $\frac{dx}{dt}$.

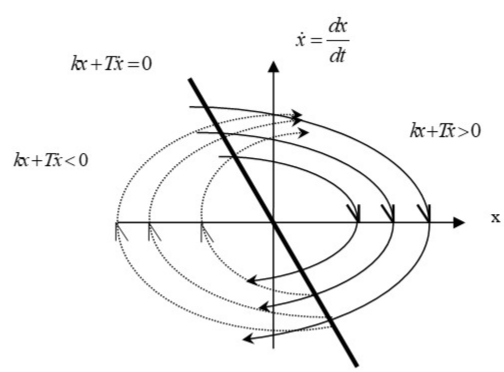


Fig. 4. *Phase plane division*

Similarly, from equation (4), integrating both sides, after transformation we have:

$$x = \frac{T}{2}\left(\frac{dx}{dt}\right)^2 + k_2 \quad (5)$$

According to the dashed parabola, the phase trajectory goes from B to point C, then meets the line $kx + T\dot{x} = 0$ Then it changes to a solid parabola, ... Just like that, we can build a complete phase trajectory of the system from starting point A as shown in Figure 5

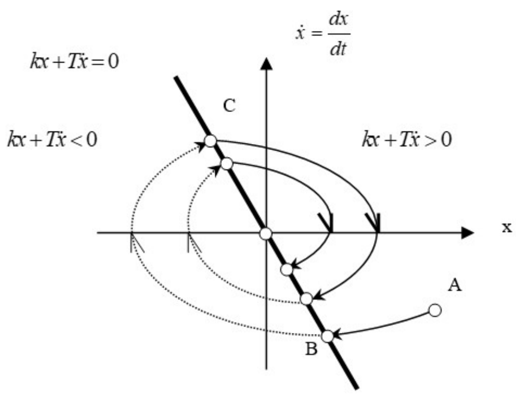
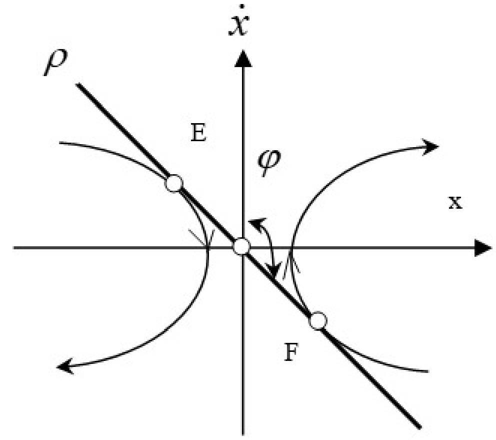
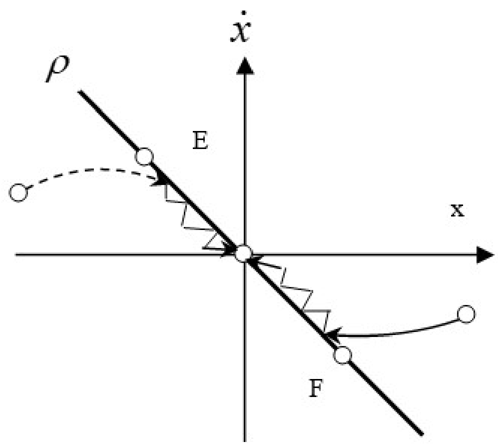


Fig. 5. *Construction of phase trajectory*

In addition, the system also has a very characteristic phenomenon called sliding or chattering phenomenon. This phenomenon appears when the phase trajectory enters the part of the bisecting line ρ, where the dashed parabola will no longer lie below ρ and the solid parabola will no longer lie above ρ. That is the line segment on ρ located between the contact point E of ρ with the solid parabola (Figure 6a) and the contact point F of ρ with the separated parabola (Figure 6b).



(a) Determine the sliding range



(b) Phenomenon of sliding phase trajectory towards the origin

Fig. 6. *Diagram explaining the sliding phenomenon*

The phase trajectory moves zick zack around the line ρ to move towards the origin. If the two-position nonlinear link allows the transition from -1 to 1 and vice versa in a time period close to 0, the above zick-zack phase trajectory segment will have the form of sliding towards the origin along the segment EF. The sliding phenomenon will be smooth when the transition time is 0.

2.2.2. Algorithm for synthesizing a controller for nonlinear systems based on sliding mode

Design a sliding mode controller for basic systems

Consider a 2nd order system of the form:

$$\dot{x}_1 = f_1(x_1) + x_2 \qquad \dot{x}_2 = f_2(x_1, x_2) + bu \quad (6)$$
$$y = x_1$$

$f_1(x_1)$, $f_2(x_1, x_2)$ are nonlinear, smooth functions with limits.

The control problem is posed: Synthesizing control in the tracking problem.

Where $x_d(t)$ is the desired trajectory and it is a smooth function, the derivative exists.

Step 1: Consider the differential of the error signal $e = x_1 - x_{1d}$, we receive:

$$\dot{e}_1 = \dot{x}_1 - \dot{x}_{1d} \quad (7)$$

From (6), (7), deduce

$$\dot{e}_1 = f_1(x_1) + x_2 - \dot{x}_{1d} \quad (8)$$

Choose x_2 as a hypothetical control signal of the form:

$$x_2 = -k_1 e_1 + \dot{x}_{1d} - f_1(x_1) + e_2 \quad (9)$$

With k_1 is a positive constant that satisfies the dynamic requirements of the system

Substituting (9) into (8), it follows that: $\dot{e}_1 = -k_1 e_1 + e_2$ (10)

From (10) we see when $e_2 \to 0$ then $e_1 \to 0$

Step 2: From equation (10), it can be deduced: $e_2 = f_1(x_1) + x_2 + k_1 e_1 - \dot{x}_{1d}$ (11)

Derivative of both sides of equation (11): $\dot{e}_2 = \frac{\partial f_1(x_1)}{\partial x_1}\dot{x}_1 + \dot{x}_2 + k_1\dot{e}_1 - \ddot{x}_{1d}$

$$\dot{e}_2 = \frac{\partial f_1(x_1)}{\partial x_1}[f_1(x_1) + x_2] + f_2(x_1, x_2) + bu + k_1(-k_1 e_1 + e_2) - \ddot{x}_{1d}$$

(12)

Then, if we choose the control signal u such that: $u = -Msign(e_2)$ (13)

$$\rightarrow \dot{e}_2 = \frac{\partial f_1(x_1)}{\partial x_1}[f_1(x_1) + x_2] + f_2(x_1, x_2) + k_1(-k_1 e_1 + e_2) - \ddot{x}_{1d} - Msign(e_2)$$

(14)

The amplitude value of M is chosen so that it satisfies the condition for the appearance of sliding mode on the sliding surface $e_2 = 0$. That is, when we choose the function $V \frac{1}{2} e_2^2$ and $\dot{V} \le 0$

$$\dot{V} = e_2 \dot{e}_2$$
$$= e_2 \left\{ \frac{\partial f_1(x_1)}{\partial x_1}[f_1(x_1) + x_2] + f_2(x_1, x_2) + k_1(-k_1 e_1 + e_2) - \ddot{x}_{1d} - Msign(e_2) \right\}$$
$$\dot{V} \le 0 \Leftrightarrow e_2 \{ \frac{\partial f_1(x_1)}{\partial x_1}[f_1(x_1) + x_2] + f_2(x_1, x_2) + k_1(-k_1 e_1 + e_2) - \ddot{x}_{1d} - Msign(e_2) \} \le 0$$
$$\Leftrightarrow M \ge \left| \frac{\partial f_1(x_1)}{\partial x_1} \right| (F_1 + X_2) + F_2 + k_1^2 e_1 + k_1 e_2 + \ddot{X}_{1d}$$

(15)

Thus, when choosing control (15) with M as a positive constant, satisfying (15) will be guaranteed $e_2 \to 0,\ e_1 \to 0$

3. RESULTS

Design of rotary drive system, moment of inertia of load: Turning radius $r_l = 0.2m$, weight $m_l = 10Kg$. The independently excited one-way actuator motor has the following parameters:

$$R_u = 5\Omega \qquad L_u = 200mH$$
$$K_b = 0.1V/rad/\sec \qquad K_i = 0.1Nm/A$$

Transmission ratio $\dfrac{N_1}{N_2} = 1/50$

Rotor's moment of inertia $J_{rotor} = 2.10^{-3} Kg.m^2$

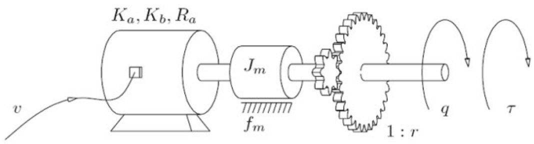


Fig.7. *Model of DC motor and speed changer*

Suppose we can only measure the rotation angle on the motor shaft.

Applying the presented algorithm, we can synthesize the control law according to the following steps:

Build system function diagram

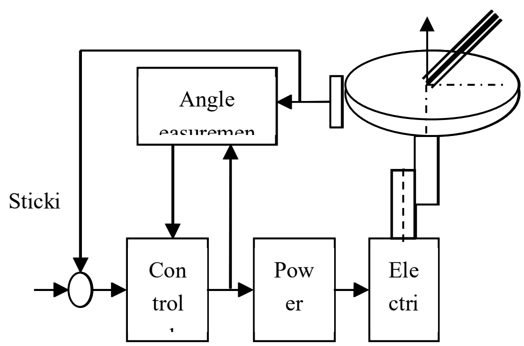


Fig. 8. *Functional diagram of the non-elastic tracking drive system*

Calculate and build mathematical models

Set state variable:

$x_1 = \theta$ rotation $\quad x_2 = \dot{\theta}$ angular velocity $\quad x_3 = i_u$ armature current

We get the equation in state space $X = [x_1\, x_2\, x_3]^T$

$\dot{x}_1 = x_2$; $\quad \dot{x}_2 = \dfrac{K_i}{J_{eq}} x_3$;

$$\dot{x}_3 = -\frac{K_b}{L_u} x_2 - \frac{R_u}{L_u} x_3 + \frac{1}{L_u} u$$

Write in matrix form: $\dot{X} = AX + Bu$

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & \dfrac{K_i}{J_{eq}} \\ 0 & -\dfrac{K_b}{L_u} & -\dfrac{R_u}{L_u} \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ \dfrac{1}{L_u} \end{bmatrix}$$

Summary of control laws

1. Build a status response rule of the form: $u = -KX$

In there: $K = [k_1 \quad k_2 \quad k_3]$

By identifying the two equalities, we can find the terms of the matrix K

$$\begin{cases} (25 + 5k_3) = 12 \\ 46.296(0.5 + 5k_2) = 22 \\ 231.48k_1 = 20 \end{cases} \qquad \begin{cases} k_3 = -2.6 \\ k_2 = -0.005 \\ k_1 = 0.0864 \end{cases}$$

2. Synthesis by backstepping - sliding algorithm

Through the transformation steps we get

$$\dot{e}_1 = -c_1 e_1 + e_2 \qquad \dot{e}_2 = -c_1^2 e_1 - (c_2 - c_1) e_2$$

$$\dot{e}_3 = -\bar{c}_1 e_1 - \bar{c}_2 e_2 - \bar{c}_3 e_3 + G(\dot{x}_{1d}, \ddot{x}_{1d}, \dddot{x}_{1d}) + \bar{b} u$$

The control law has the form: $\bar{b} u = -c_3 sign e_3$

Simulation results:

Simulation diagram in MATLAB-SIMULINK environment (Figure 9)

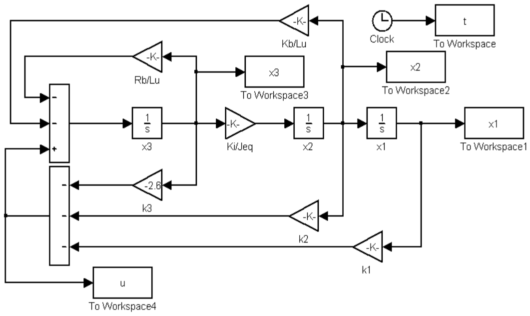


Fig. 9. *Simulation diagram when synthesizing state feedback with signal set to 0*

Simulation results: shown in figure 10:

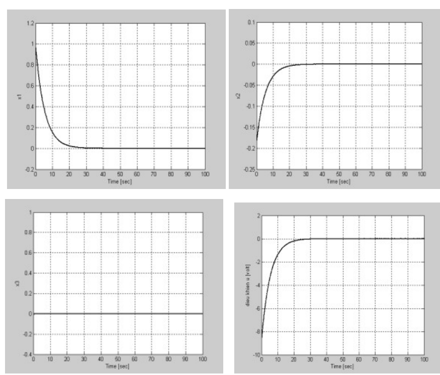


Fig. 10. *Simulation results with state feedback*

Simulation diagram when synthesizing control using the Backstepping - sliding method combined with a sliding observer.

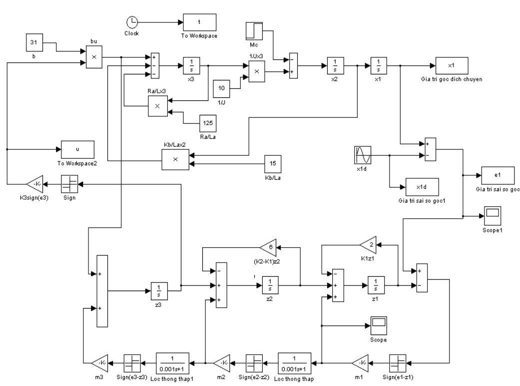


Fig. 11. *Backstepping-sliding control synthesis simulation diagram*

Desired trajectory: $x_{1d}(t) = \sin t[rad]$

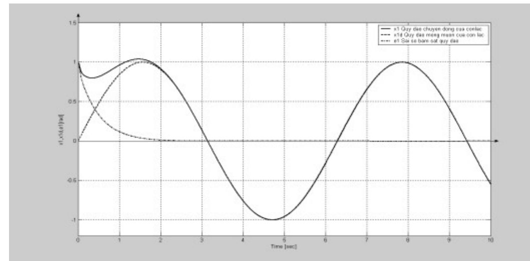


Fig. 12. *Motion trajectory $x_1(t)$ follow the desired trajectory $x_{1d}(t)$ and error closely*

$e_1(t) = x_1(t) - x_{1d}(t)$ with initial value $x_{01}(0) = 1$

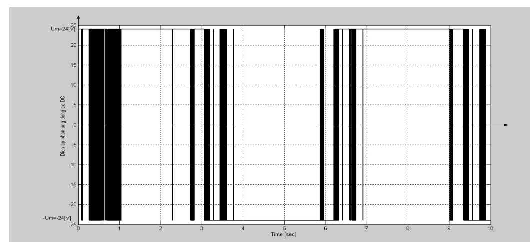


Fig. 13. *Control voltage applied to the armature of a DC motor*

Comment: The simulation results work well, proving the correctness of the synthesis algorithm. However, it is necessary to experiment on a physical device to test more accurately.

CONCLUSION

The control theory of a system with a variable structure is a difficult theory, based on the theory of differential equations with a discontinuous right-hand side. The sliding control method needs to be studied in more detail so that it can be applied to synthesize controllers for non-linear, non-stationary systems, under the motion of unknown components, disturbances...

Synthetic method of control in sliding mode, applied in 1st, 2nd, 3rd order electromechanical systems as a basis to solve the problem of tracking control in DC electric drive systems.

Lesson development directions include: Using the above control algorithms in the process of analyzing and controlling DC motors based on the sliding control method; To ensure optimal control as well as system quality, it is necessary to experiment with the above method on a real physical model; Expand the study of the above control algorithms when considering the image of frictions in the system.

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