SLIDING MODE CONTROL FOR AN ELECTRORHEOLOGICAL FLUID ACTUATOR

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Abstract

The present paper discusses a sliding mode control method suitable for solving the control problem of hydraulic position servos with a flexible load. The statement of problems is briefly given, and sliding mode control design for this model is discussed in detail. The hydraulic actuation of the system is based on electrorheological fluid. The electrorheological fluids are controllable fluids in electrical field, whose apparent viscosity can be dramatically changed according to an electrical voltage applied to the device. The real goal of this work is to model an electrorheological actuator using the sliding mode control.

Keywords: sliding mode control, electrorheological fluid actuator, and hydraulic actuation.

1. INTRODUCTION

Electrorheologial fluids are the fluids whose apparent viscosity can be modify by application of a high strength electrical field, of the kV/mm order. Such materials have been studied more or less empirically still since XIIX century, by Priestly and Winckler, but the first rigorous scientific study was effected by Winslow in 1947 (Weiss, 1992). This used a starch suspension or silicon gel in mineral oil. The study carried out by Winslow showed the fact within the application of a 4 kV/mm electrical field takes place a sudden increase of the viscosity of the electrorheological fluid. Since then many applications have been developed in more engineer fields. Among these applications are remarked: dampers, clutches, tentacle robots, machines and hydraulic operation machines etc.

The electrorheological effect, named, also, Winslow effect consists in the dramatic modification of the fluid rheological properties, namely the viscosity. This effect is due to the difference between the dielectric constants of the main fluid, which is insulating, and the suspension particles. Thus, during the application of the electrical field, the conductor particles of the suspension will form chains owing to the induced dipole moment.

Corresponding to the study worked out by Winslow regarding this effect, the electrorheological effect corresponds to the fibrillation of the electrorheological fluid during application of the electrical field. He suggested the reciprocal attraction among the conductor particles (which are in mineral nonconductive oil with low viscosity), during the application of the field produces the chains of particles between electrodes. Thus, in the presence of the shear stress, the balance that sets between the formations of particles and the breaking of the interelectrode chains corresponds to a Bingham plastic model. When the electrical field is canceled, the particles return to an aleatory distribution, allowing the taking again of the fluid flowing.

2. THE PROPOSED MODEL

A viscous fluid which presents yield stress, as it is certain electrorheological material, can be model as Bingham plastic. This model is described by the equation:

$$\tau = \tau_y + \eta \dot{\gamma}, \qquad (1)$$

where τ is the shear stress,
τ_y is the yielding shear stress,
η is the plastic viscosity, and
$\dot{\gamma}$ is the shear rate.

The model used for the research in this article is made up by three elements (Powell, 1995) that describe completely how these intelligent materials work. This model is presented in Fig.1. The elastic element is viewed nonlinear because the behavior of the electrorheological material is influenced not only by applied force, but the electrical energizing field.

3. SLIDING MODE CONTROL

We shall take into account the model proposed in Fig.1 included in a control loop of a robotic joint. This robotic joint will be driven by a hydraulic actuator (Handroos, Liu, 1998), which uses as work fluid an electrorheological material.

In Fig.2 is described the schematic diagram of the joint. We used the following notations here:

x_p is the rigid position of the piston,

x_l is the flexible position of the load,

m_1, m_2 are the masses of the rigid fixed load, respectively,

A_1, A_2 are the two areas of the piston in the room 1 and room 2, respectively,

k is the elastic constant,

b is the damping factor between the 2 interconnected loads,

c is the factor of viscous friction,

p_1, p_2 are the pressures in the 2 rooms of the piston,

p_s is the pressure of the fluid source,

i is the electric current applied to the valve.

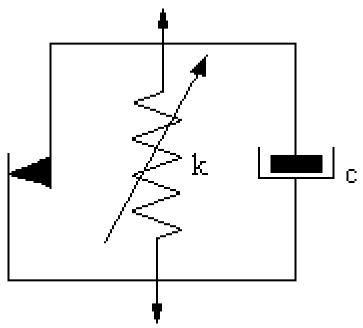

Fig. 1

Now, we use the following notations:

$$\begin{cases} x_1 = x_l \\ x_2 = \dot{x}_l = \dot{x}_1 \\ x_3 = x_p \\ x_4 = \dot{x}_p = \dot{x}_3 \\ x_5 = p_1 \\ x_6 = p_2 \end{cases} \qquad (2)$$

and we assimilate them as state variables. We define the pressure of the load like this:

$$\hat{x}_5 = p_1 - \frac{A_1}{A_2} p_2 \qquad (3)$$

Thus, we considered that the following vector describes the state vector of hydraulic position servo with flexible load:

$$x = \begin{bmatrix} x_1, & x_2, & x_3, & x_4, & \hat{x}_5 \end{bmatrix}^T \qquad (4)$$

Now, it follows to declare the problem of the control of this system. The controller for the sliding mode was designed so that the vector of operating state from the equation (4) should follow asymptotically a desired state vector $x_d = \begin{bmatrix} x_{1d}, & x_{2d}, & x_{3d}, & x_{4d}, & \hat{x}_{5d} \end{bmatrix}^T$, which is predetermined by finite control input i in the presence of the parametrical uncertainty of the system. Mathematically, we can, also, put this in following form:

$$\lim_{t \geq t_0} (x - x_d) = 0 , \qquad (5)$$

where $t_0 > 0$ is the response time of the systems whose errors of steady state are null.

In the Fig.3 is shown the block diagram of control system. The apparent viscosity of the fluid can be easy modified by application of an energizing electrical field (Ivanescu, Stoian, 1998), like this:

$$\eta = \eta_0 + \frac{\tau(E)}{\dot{\gamma}} , \qquad (6)$$

where $\tau(E)$ is the unitary stress as a function of electrical field applied E, and

η_0 is the viscosity at zero field.

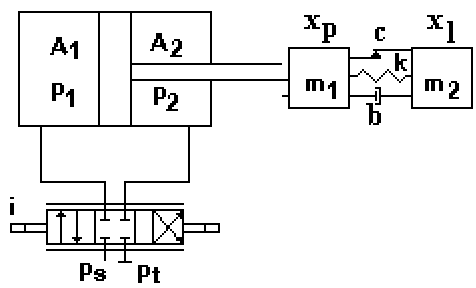

Fig. 2

We consider that the viscosity is checked up only periodically at the application of the electrical field. The errors of the systems are defined in the this way:

$$e_i = x_i - x_{id} , \quad cu \quad i = 1,...,4 \qquad (7)$$

$$e_5 = \hat{x}_5 - \hat{x}_{5d} \qquad (8)$$

The desired trajectory x_{3d} of the piston position is defined previously in order to be used as reference input of control system. The corresponding desired speed $\dot{x}_{3d}$ is obtained by the derivation of the trajectory equation, x_{3d}. We can obtain the desired trajectory of the position of the flexible load x_{1d} and its speed $\dot{x}_{1d}$ by the designing of the reference model as follows:

$$x_{1d} = \frac{\omega^2}{s^2 + 2\delta s + \omega^2} \cdot x_{3d} \qquad (9)$$

$$\dot{x}_{1d} = \frac{s\omega^2}{s^2 + 2\delta s + \omega^2} \cdot x_{3d} \qquad (10)$$

where s is the Laplace operator.

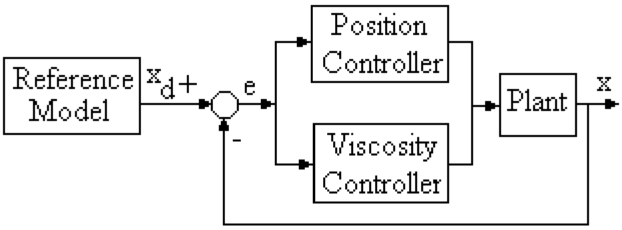

Fig. 3

The parameter $\hat{x}_{5d}$ is obtained by the resolving of the equation (8). In order to obtain that the all system states follow the desired trajectory equations at the same time, the function of the sliding surface (Ivanescu, Stoian, 1998) is defined like this:

$$S = \dot{e} + N \cdot e \text{ , cu } N > 0 \qquad (11)$$

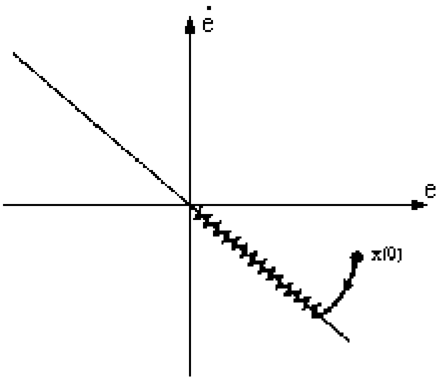

Fig. 4

where the error e is defined in the following way:

$$e = w_1 \int e_1 dt + w_2 e_1 + w_3 \int e_3 dt + w_4 e_3 + w_5 \int e_5 dt \qquad (12)$$

The values w_i are the multiplier gains. In Fig. 4 it is represent a diagram of a sliding surface. The selection of one multiplier gain depends on the part of the error, which is more important in this system. Here, it is paid a greater attention to the error of the load position.

Now, we are defining the following Lyapunov function in such manner:

$$V = \frac{1}{2} S^2 \geq 0 \qquad (13)$$

that is a quadratic form, positive defined. The Lyapunov stability condition is the following:

$$\dot{V} < 0 \text{ ,} \qquad (14)$$

the expression which represents the condition of attraction for the control in sliding mode control. Now, we proposed the global sliding mode control law at this type:

$$i = \hat{i}_{eq} - k \cdot \operatorname{sgn}(S), \qquad (15)$$

where i_{eq} is the equivalent law control,

k represent the switching gain that is used so that it should guarantee a sliding mode control on the switching surface $S(t)$. The control law is made up of 2 terms, which are described by the equivalent control and switch control, respectively.

In order to reduce the magnitude of chattering in the input control signal, instead of function $\operatorname{sgn}(S)$ from the relation (15) is used the function $sat(S)$, the saturation function (Asada, 1986). Mathematically, this function is described in the following way:

$$sat(S) = \begin{cases} 1, & S > \varepsilon \\ \dfrac{S}{\varepsilon}, & -\varepsilon \leq S \leq \varepsilon \\ -1, & S < \varepsilon \end{cases} \qquad (16)$$

where the parameter $\varepsilon > 0$ is the width of boundary layer in S (see Fig. 5).

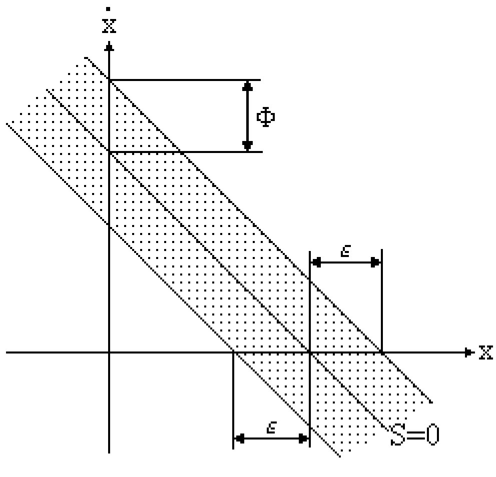

Fig. 5

During the transient phase of the dynamics, S may move in and out of this boundary. However, once the Lyapunov stability criterion is satisfied, S remains entrapped in this layer. In the process of design for sliding mode control, it is very important to choose the suitable control parameters, such as k, ε, and weighting gains. Because of the nonlinear system, there is no regular method to determine these values.

4. CONCLUSIONS

This work presents the sliding mode control for an electrorheological valve used at the robotic joints. It was proposed a model with 3 elements for the work fluid, a model that takes into account the elasticity of the electrorheological material, the viscous friction and, no in the last place, the damping that occurs between the piston (the fixed element) and the load (the flexible element). This kind of control is robust, and the control system contains two control loop: one for the position control, and the other for the control of the viscosity of the electrorheological material.

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