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Improved sliding-mode control for servo-solenoid valve with novel switching surface under acceleration and jerk constraints

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The nonlinear sliding-mode (SLM) controller based on the maximum jerk and time-optimal step response has been developed for the control of servo-solenoid valves, which exhibits its performance advantages when compared to traditional PID controller. However, the experiments shows the responses of the SLM control under only jerk constraint will largely vary with different damping and loads, leading to the large overshoot and breakdown under some working conditions (e.g., large viscous damping coefficient). Thus, an improved SLM controller is developed in this paper to deal with the existing drawbacks, where a novel nonlinear SLM surface is proposed by taking into account both spool's acceleration and jerk limitation. Firstly, the nominal model of servo-solenoid valve is built by linearizing the dynamics on the null position, and the system identification is carried out to achieve the model parameters and their variation ranges. Subsequently, the valve constraints under the power limitation are analyzed through the frequency response of the identified model, which comes out the maximum available velocity, acceleration and jerk. Finally, the improved SLM control algorithm is proposed, where the novel SLM surface considers the maximum plus jerk, the maximum minus jerk and the maximum acceleration. Experimental studies are conducted and the results show that the improved SLM controller under both acceleration and jerk constraints can achieve the continuous and stable sliding mode state, realize the time-optimal step response of the valve, and exhibit strong disturbance rejection abilities.

1. Introduction

Servo valves have the advantages of high accuracy and fast response, but the contamination sensitivity and high price hinder their wide application. The characteristics of the proportional valves are the opposite, which are suitable for low requirements for precision and response. Thus, servo-solenoid valves (SSV) which own both advantages of servo valves and proportional valves, have been successfully developed in these years and widely used in industrial applications [1–3]. A typical SSV shown in Fig. 1 is usually zero lapped, actuated by a high-performance solenoid, and mounted with an inductive position transducer (e.g. LVDT) by which the spool's position can be measured as a feedback control signal [4].

Besides the electro-mechanical converter, the dynamical performance of SSV is usually limited by its feedback controller. Maximizing the hardware driving potential and dealing with the disturbances such as flow-force and friction are two challenging issues for the high performance control design. Recently, various advanced control strategies such as backstepping control [5,6], H-infinity control [7], adaptive control [8], disturbance observer [9], adaptive robust control [10–12], predictive control [13,14], neural network and fuzzy control [15,16] are developed for hydraulic or relative mechatronic systems, and some of them are further applied to improve the servo-solenoid valve performance. Bu and Yao [17,18] synthesize three types of controller including pole/zero cancelation, full state feedback adaptive robust controller and output feedback adaptive robust controller to improve the valve performance, but the further improvement is restricted by the high nonlinearity and fast time-varying unknown parameters. Ohsumi et al. [19] design a disturbance observer to compensate the time-varying load and friction, and significantly improve the valve response to the range of 0.5% prescribed value. In [20], Boes et al. introduce a new servo valve with integrated digital controller and fieldbus interface. The fault diagnosis and the closed loop control of spool's position or pressure output could be realized easily by the software tuning. Li et al. [21] propose a hybrid control scheme, which consists of PID controller, feed-forward compensator and

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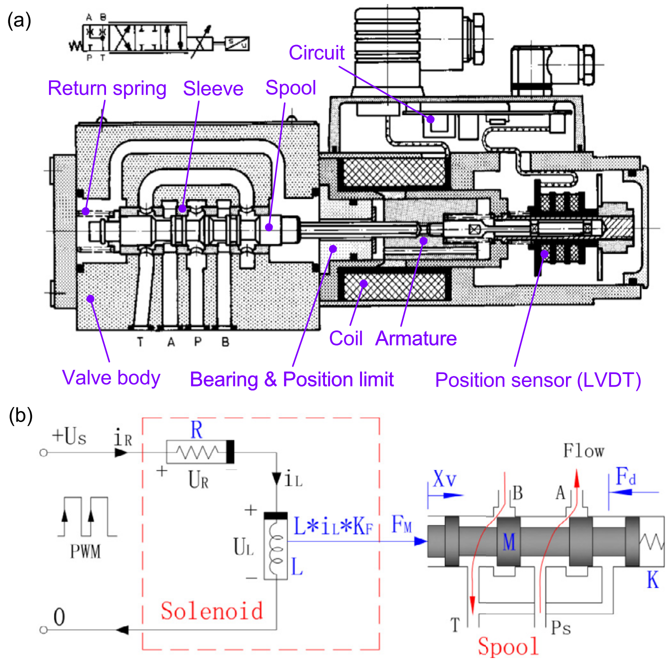

Fig. 1. Servo-solenoid valve: (a) Sectional drawing; (b) Equivalent diagram.

disturbance observer, to improve the performance of a voice coil motor driving high-pressure pneumatic servo valve. Pan et al. [22] exploit the variable structure method and sliding mode observer to control the opening angle of a throttle valve with the existence of non-smooth nonlinearities, parameter uncertainties and disturbance. A controller based on approximate model and uncertainty compensation is proposed by Yuan et al. [23] and applied to the control of electronic throttle valve. In [24], a robust nonlinear control approach is utilized in the position control of a pneumatic valve with unknown friction, and the limit cycling and hunting phenomenon are successfully avoided. In [25], the power and control electronics are designed for the servo-valve actuated by piezoelectric motor. Acceptable performance and low-consumption are fulfilled together so that the valve is suitable for aeronautic applications. Miyajima et al. [26–28] develop a control algorithm for pneumatic servo valve, including a calculation delay compensator and a disturbance observer, which leads to the dynamic response increasing up to 300 Hz. Gamble and Vaughan [29–31] employ the sliding mode control method and propose a nonlinear switching surface which represents the optimal trajectory for step input under the jerk limitation. Some sliding mode control improvements are introduced in [32] from the view of practical applications, including integral element, velocity feedforward, high voltage supply, and LVDT modifications. The dynamic response and the disturbance rejection ability are improved effectively.

However, under some working conditions (e.g., large viscous damping coefficient), the existing sliding mode control of servo-solenoid valve [29–31] based on the maximum jerk only may show some performance drawbacks such as large overshoot and breakdown in the experiment. The essential reason of these phenomenons is that in here the acceleration constraint will also take important effects for the system response. In this paper, the dynamic constraints of the valve's movement including velocity, acceleration and jerk are discussed and comprehensively analyzed by the frequency responses of the SSV under two different situations. To deal with the performance drawbacks of the existing controllers in [29–31], an improved sliding mode control design by a novel switching surface is developed which takes into account both the spool's acceleration and jerk constraints. Thus, the good dynamic response and strong disturbance rejection ability of the SSV are fulfilled under both situations. The experimental results show the better performance and verify the effectiveness of the proposed control method.

2. Nominal model of SSV and identification

The linearized model of the servo-solenoid valve around null position can be expressed in the following [29]. The equivalent diagram of SSV is shown in Fig. 1(b).

$$x_v(s) = \frac{1}{ms^2 + bs + k} * \left[\frac{K_{F0}}{s + R/L_0} \Delta u(s) - F_d(s) \right] \tag{1}$$

where x_v is the spool displacement; Δu is the incremental voltage acting on the solenoid; K_{F0} is the electromagnetic-force gain coefficient at null position; L_0 is the inductance of the coil at null position; R is the equivalent resistance of the coil; m is the combination mass of the spool and armature; b is the viscous damping coefficient; k is the stiffness of return spring; F_d represents the external disturbance force, mainly including the coulomb friction, transient flow force, and steady-state flow force which is the main load of the spool movement.

Thus, the transfer function of the servo-solenoid valve from Δu to x_v is

$$\frac{x_v(s)}{\Delta u(s)} = \frac{K_{F0}}{(s + R/L_0)} * \frac{1}{(ms^2 + bs + k)} \tag{2}$$

Since the SSV adopts the structure of single solenoid and return spring, the return spring should be with a considerable preload force when the spool is at the null position. The preload force is measured to be 90 N, and the corresponding current in the solenoid needed to balance this force is about 2 A, which is referred to as standing current. Assume the resistance of the solenoid and the wire is 3Ω, and the power voltage supply is 24 V, then the incremental voltages Δu in two directions around the null position are 18 V and 30 V respectively [32]. Obviously, Δu in two directions are asymmetrical, so in the controller design, it can only conservatively choose the smaller value.

The sliding mode control method based on the relay on-off switching control is used in this study. The voltage exerted on the solenoid is similar to the PWM wave. The voltage will produce ripple in the driving current, which has chatter effect and can eliminate part of the hysteresis. Therefore, the effect of hysteresis is ignored in the above model. The electromagnetic-force gain coefficient K_F and inductance L are strong nonlinear, and they are both the functions of flux linkage Ψ and spool displacement x_v (equivalent to the length of air gap). The curves which reveal these functional-relationships could be found in Fig. 2, according to the experimental results. These curves illustrate the linearized value of K_F and L around the null position, and also indicate the variation ranges of parameters between two limited spool displacement (±2 mm) when exclusively considering the spring force. Note that the variation ranges will become wider if the external loads are taken into account.

In the spool model, the mass m and the spring stiffness k can be directly measured. The viscous damping coefficient b can be calculated indirectly with the SSV simulation model, spool's movement measurements (displacement, velocity and acceleration), as well as the above known parameter values. The viscous damping coefficient is affected by several factors, such as the oil viscosity, the volume of oil keeping in the solenoid chamber. When the oil is added into the valve just for lubrication and the valve is unloaded, b is calculated to be 40 Ns/m. When the chambers of solenoid and valve are full of oil, b is calculated to be about 200 Ns/m.

The key parameters of SSV are shown in Table 1, which are obtained in the practical experiments by linearizing the SSV model