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Technical note

Control-oriented friction modeling of hydraulic actuators based on hysteretic nonlinearity of lubricant film☆

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ABSTRACT

Friction modeling of hydraulic actuators is essential to system control and the prediction accuracies of friction models (e.g., Stribeck, LuGre) need to be improved when they were applied to hydraulically actuated systems. The test platform for hydraulic cylinders was constructed and the friction forces of plunger type hydraulic actuators were measured under different operating conditions. The dynamic behaviors of film thickness of seal/rod interface were investigated based on elastic hydrodynamic lubrication (EHL) method. The effects of acceleration of rod on friction force were examined using coherence function estimation technique. The Stribeck and LuGre model were modified by incorporating physically based hysteretic film dynamics and Bouc–Wen model into Stribeck function, respectively. It is shown that the Stribeck and LuGre model cannot preferably describe the friction force-velocity behavior, especially for the fluid lubrication regime. The modified Stribeck and LuGre model can simulate the hysteretic behavior of friction force-velocity loop more effectively than unmodified ones and the friction estimation accuracies of Stribeck and LuGre model were improved remarkably.

1. Introduction

Hydraulic actuators are widely used in various branches of industry applications, because of high power-to-weight ratio, self-lubricating, high stiffness, long operating life, wide speed-regulating range, etc. However, the control performance of hydraulic actuators has been challenged, due to the existence of friction.

A suitable friction model is necessary to predict the motion of mechanical system, analyze stability, design control schemes (regulating controller gains or friction compensation), etc. In the control practice of high precision hydraulic positioning systems, friction force of the actuator cannot be ignored during control strategy design, since it has a significant effect on dynamic characteristics of the system.

In this regard, it is certainly worth establishing an accurate macroscopic control-oriented friction model in order to provide a theoretical basis for real time control of hydraulic systems.

Several mathematical friction models have been established to describe friction characteristics. The well-known Coulomb and viscous friction model are commonly used in engineering, e.g., friction characterization of actuators mounted on the electro-hydraulic Stewart platform for motion simulator [1]. The German scholar, Stribeck, discovered the relationship between velocity and friction coefficient in the experiment of friction test of bearings. Subsequently, Bo and Pavelescu [2] proposed a friction model of what came to be known as Stribeck model, based upon Stribeck curve by using an exponential model to describe the negative friction-velocity gradient phenomenon. Stribeck model has been extensively used over a long period of time in friction modeling, identification, stability analysis and position tracking [3–5]. Karnopp [6] added an interval around the neighborhood of zero to viscous friction model to overcome the difficulty of zero speed detection in simulation and system control. However, the aforementioned friction model is useful in steady state, it is inadequate to predict dynamic performance of mechanical system [7], particularly in the situation that the variation of instantaneous velocity is great in one operation cycle.

A dynamic friction model which describes the asperities of contact interface as spring, was proposed by Dahl [8]. Dahl model introduces pre-sliding displacement into friction model, and solves the problem of non-discontinuous in status switching of static friction model. Moreover, Dahl model can predict the friction lag characteristic, but it is unable to describe the Stribeck effect. Armstrong-Hélouvry [3] presented an integrated seven parameter friction model on the basis of a

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friction model that characterizes the relationship between break away force and dwell time. Hess and Soom [9] examined the friction-velocity behaviors under unsteady velocities which covered different lubricated regimes. It is shown that friction demonstrates different values during acceleration and deceleration period and this can be modeled by a characteristic time lag between a varying velocity and the corresponding friction. Haessig and Friedland [10] introduced the bristle model to capture the stochastic behavior of microscopic friction phenomenon in contacting interfaces. However, the model is inefficient numerically because of its complexity [11] since a very short time step is essential in real time calculation. In addition, a discontinuous variable is introduced in this model, thereby restricting its application.

LuGre model [12] is a very important milestone in the development of friction model. In this model, friction is expressed as the average deflection force of a large number of random bristles, and most of the friction characteristics in mechanical systems, such as friction lag, Stribeck effect, pre-sliding, etc., can be described via using this model [13,14]. Therefore the LuGre model is widely applied in various fields and different forms of expressions of modifications are proposed [7–18]. Yanada and Tran [7,15] investigated the friction behaviors of hydraulic cylinders under different magnitudes of external load, and proposed a modified friction model of hydraulic cylinders by incorporating lubricant film effects into LuGre model. The modified LuGre model can describe dynamic friction characteristics with a good accuracy, which is of great significance to the prediction of the motion of hydraulic cylinders and high precision control of hydraulically actuated system. Ylinen [17] modeled the friction of hydraulic cylinders as a product of pressure related linear dimensionless scaling factor and friction force in the form of LuGre model.

In order to describe the complete friction characteristics obtained by experiments, the Leuven model and its modification were demonstrated by Swevers and Lampaert [19,20]. In the Leuven model, a hysteresis function was incorporated to describe sliding and presliding friction behaviors and a good accuracy was obtained in characterizing friction behaviors, such as Stribeck effect, frictional lag, and hysteresis behavior of a linear slide. In [20], the Leuven model was modified to overcome the discontinuity during transition and stack flow which occurs in real time implementation. Dupont et al., [21] presented an elastoplastic friction model and it is used in the friction compensation of fine-positioning linear axis [22]. Al-Bender [23] proposed a generalized Maxwell-slip (GMS) model by mimicking physical mechanism, in which multiple parallel Maxwell elements are assembled. The GMS model imposes a spring behavior and a weighted Stribeck effect on sticking and slipping phase of each Maxwell-Slip block, respectively.

Although much efforts have been made to characterize friction behaviors, there have been lots of drawbacks need to be overcome for friction models that are expected to be applied in engineering. For instance, the friction models Dahl, LuGre, Leuven, GMS model are not able to describe the complete friction behaviors during acceleration and deceleration motion, in terms of friction modeling of TSM [24].

The aforementioned friction models are often utilized in the control of hydraulic systems with friction. The viscous and Coulomb friction model are commonly used for the description of friction force of hydraulic control systems, such as hydraulic actuators [25–27], hydraulic rotary motors [28,29], hydraulically actuated dynamic robots [30,31], multi-DOF hydraulic manipulators [32], hydraulic excavators [33], etc. Due to the incompleteness in describing friction characteristics for viscous friction and Coulomb friction model, the unmodeled friction forces are usually lumped into the disturbances or uncertainties [34,35]. Thereby, a disturbance observers are often designed in order to guarantee the asymptotic stability in Lyapunov sense [36–38].

In the case of high-precision trajectory tracking, model-based control strategies depend on the accuracy of friction model in a sense, since nonlinear friction leads to considerable negative effects on system's control performance. Because of the inaccuracy of viscous friction and Coulomb friction model, the control schemes designed tend to be conservative when disturbance observers are utilized to mimick the unmodeled friction force. Control schemes that intend to compensate for the negative influences of nonlinear friction, without adopting high gain control loops inherently require an accurate friction model to estimate and to compensate for the friction force [12].

Due to the simplicity of LuGre friction model, it is the most widely used friction model in the control of electro-hydraulic systems [39–41], especially in the case of friction compensation [42,43]. Often, the adaptive control strategy [44,45], slide mode control method [46], backstepping method [47] are used in friction compensation incorporates friction observer based upon LuGre model. Experiments show that the friction force-velocity hysteretic phenomenon exists in the fluid lubrication regime in which the hydraulic cylinder is actuated in high velocities. Static friction models, e.g., the integration of Coulomb friction and viscous friction, are not sufficient to describe the exact dynamic friction behaviors, e.g., the aforementioned friction force- velocity behavior, even at higher velocity ranges. And the effects of hydraulic pressures on friction force of hydraulic cylinder have not been made clear and the rationality of incorporating hysteretic film dynamics and acceleration into the friction models remains to be investigated.

In this paper, the dynamic friction behaviors of plunger type hydraulic actuators were investigated under varied velocities and pressures. The effectiveness of describing actual friction characteristics for Stribeck and LuGre model during acceleration and deceleration motion for hydraulic cylinder was evaluated. The rationality of incorporating lubricant film dynamics into friction models was validated using EHL method. The dependency between friction force of hydraulic actuators and acceleration was investigated and the rationality of incorporating acceleration into friction models was validated using coherence functions analysis. The aforementioned investigations are a prerequisite to the modification of friction models by taking lubricant film dynamics and acceleration into account. Moreover, modified Stribeck and LuGre model with fewer parameters compared to previously developed modified LuGre model, were proposed to describe the friction-velocity hysteresis behavior using physically based model lubricant film dynamics and Bouc–Wen model, respectively, based on the concept of Yanada [7]. The simulated results of proposed friction model and experimental results were compared.

2. Experimental setup

2.1. Experimental apparatus

The schematic of the experimental setup is presented in Fig. 1. The entire system was powered by two hydraulic pumps, which deliver fluid to main cylinder (plunger type hydraulic actuator, labeled as A) and load cylinder (plunger type hydraulic actuator, labeled as B), respectively. The main and load cylinder, of which rod diameter and stroke

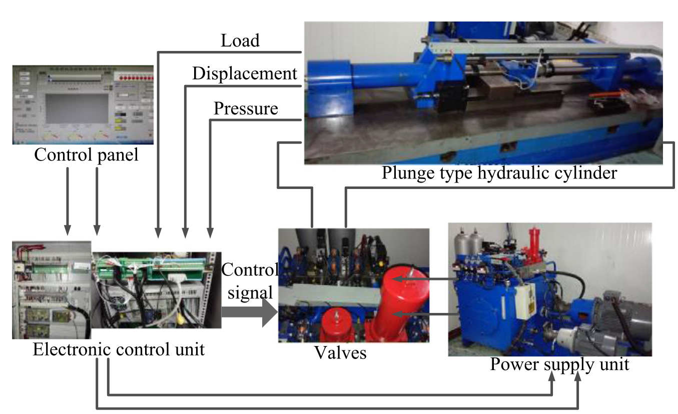

Fig. 1. Experimental setup of the hydraulic actuators.