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# Comparison of friction models applied to a control valve

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**Abstract**

Eight different models to represent the effect of friction in control valves are presented: four models based on physical principles and four empirical ones. The physical models, both static and dynamic, have the same structure. The models are implemented in Simulink/Matlab® and compared, using different friction coefficients and input signals. Three of the models were able to reproduce the stick-slip phenomenon and passed all the tests, which were applied following ISA standards.


*Keywords:* Control valves; Stiction; Stick-slip; Static friction models; Dynamic friction models; Data-driven models

## 1. Introduction

Performance assessment of control loops is an important research theme, and there are many tools to detect variability in control loops. These tools are employed to diagnose different causes of variability, such as friction in the control valve, oversized valves, improperly tuned controllers, disturbances coming from other control loops, and so on. Data extracted from real processes is usually used to test the performance assessment tools. An easier way to perform the initial tests of the performance assessment techniques might be to use simulators, in which the cause of variability is simulated. After these preliminary tests, the tool can be applied to diagnose real situations with data collected from existing plants.

Control valves are the most common final control elements in industry. One of the main factors that affect the behavior of the control loops is friction in control valves. Among the variability causes previously mentioned, the most difficult one to model is friction, and in particular static friction (stiction). The purpose of this paper is to implement and test different friction models applied to control valves. The idea is to analyze the behavior of the models with the valve operating in open loop, simulating a valve installed in a bench.

It is necessary to take into account that valve behavior changes significantly as friction increases. Consider, for instance, an ideal frictionless pneumatic valve with a full stroke of 0–100%. If this same valve is affected by friction, it will not move until a certain pressure is applied to its actuator. Besides, when a valve is affected by stiction, the behavior of the control loop presents variability, since the valve does not respond instantaneously to the control signal. What happens is that the signal that comes from the controller has to reach a value high enough to overcome the stiction and move the stem. When this occurs, the stem slips and the valve position normally goes to a point beyond the desired value, causing oscillations and variability in the control loop.

Models based on physical principles as well as empirical or data-driven ones have been proposed to simulate valve friction. Physical models describe the friction phenomenon using balance of forces and Newton's second law of motion. The main disadvantage of these models is that they require knowledge of several parameters such as mass of the moving parts, spring coefficient, and various friction coefficients (viscous, Coulomb and static), which are not easily estimated (Garcia, 2007; Romano & Garcia, 2007, 2008). On the other hand, the data-driven models simplify

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the simulation of a sticky valve and have been used to study valve stiction (He, Wang, Pottmann, & Qin, 2007).

Many papers on friction modeling in control valves have been published in the last few years (Choudhury, Jain, & Shah, 2006; Choudhury, Thornhill, & Shah, 2004; Choudhury, Thornhill, & Shah, 2005; Eborn & Olsson, 1995; He et al., 2007; Jain, Choudhury, & Shah, 2006; Kano, Maruta, Kugemoto, & Shimizu, 2004; Kayihan & Doyle, 2000; Stenman, Gustafsson, & Forsman, 2003), but a full comparison of different models to describe the behavior of control valves affected by friction has not been presented. In Eborn and Olsson (1995) the authors compare some friction models, but the results are presented with the valve inserted in a control loop, in such a way that it is difficult to visualize how the isolated valve responds when submitted to different kinds of input signals. In He et al. (2007) the authors present one figure comparing some data-driven models, considering just the case when the valve is ideal, that is, with no friction.

In this work, the simulated valves are modeled with three different levels of friction and are submitted to tests that are recommended in ISA standards for real control valves (ISA, 2000, 2006). This form of testing the models is a contribution of this work, since there is not any other related paper that performs tests in simulated valves according to international standards.

The paper is organized as follows: in Section 2, the eight valve friction models applied to a pneumatic spring-diaphragm sliding stem valve are presented. In Section 3, the applications of the valve friction models analyzed in this paper are listed. In Section 4, the tests applied to control valves according to ISA standards are presented. In Section 5, the characteristics of three valves with different friction coefficients are presented. In Section 6, the responses of the model simulations, with valves with different friction coefficients, applying the ISA recommended testing, are shown and an evaluation table is presented. Finally, in Section 7, the conclusions are drawn.

## 2. Control valve friction models

As the main purpose of this paper is to compare friction models applied to a control valve, eight different models of friction in pneumatic sliding stem control valves are presented, starting from simple models, with just one parameter, and moving to more complex ones, with seven parameters: Classical (Olsson, 1996), Karnopp (Karnopp, 1985), Seven Parameters (Armstrong-Hélouvry, Dupont, & Canudas de Wit, 1994), Lugre (Canudas de Wit, Olsson, Åström, & Lischinsky, 1995), Stenman (Stenman et al., 2003), Choudhury (Choudhury, Jain et al., 2006; Choudhury, Thornhill et al., 2004; Choudhury et al., 2005), Kano (Kano et al., 2004) and He (He et al., 2007). The first four are physical models, the first two (Classical and Karnopp) being static models and the next two (Seven Parameters and Lugre) dynamic ones. The last four are empirical models. Notice that the more recent models are all data driven.

### *2.1. Force balance on the components of a pneumatic sliding stem valve*

The function of the valve actuator is to move the valve stem to modulate its opening. Pneumatic control valves are still the most used in the process industries, due to their low cost and simplicity. In order to model a sliding stem valve, it is assumed that the input variable is the signal that comes from the controller, converted to a pressure signal, and that the stem position is the output variable. In that way, the force balance equation is as follows (Choudhury et al., 2005; Kayihan & Doyle, 2000):

$$m \times \ddot{x} = F_{pressure} - F_{spring} - F_{friction} - F_{fluid} - F_{seat}, \quad (1)$$

where $m$ is the mass of the valve moving parts (stem and plug); $x$ is the stem position; $F_{pressure} = S_a \times P$ is the force applied by the actuator, $S_a$ being the diaphragm area and $P$ the air pressure; $F_{spring} = k \times x$ is the spring force, $k$ being the spring constant; $F_{friction}$ is the friction force; $F_{fluid} = \alpha \times \Delta P$ is the force due to the fluid pressure drop across the valve, with $\alpha$ the plug unbalanced area and $\Delta P$ the pressure drop; and $F_{seat}$ is the extra force required for the valve to be forced into the seat. Following Choudhury et al. (2005) and Kayihan and Doyle (2000), the contributions of $F_{fluid}$ and $F_{seat}$ are negligible in practical situations. $F_{fluid}$ is disregarded because it is two orders of magnitude smaller than the friction and spring forces, which means that the valve is modeled as if there was no fluid in the line. $F_{seat}$ is not considered for simplicity.

The main issue is how to model the friction force in Eq. (1). This will be done in the following sections through different friction models.

### *2.2. Static friction models*

According to Olsson (1996), friction models can be classified as static and dynamic. The classical friction models are static, which means that the friction is modeled as a static function of velocity. In the dynamic models there are time-varying parameters. This classification does not agree with what is normally defined as static or dynamic systems, but it has been kept in this work, to be in agreement with the related published papers.

In the static models, three components are normally considered:

- static friction or *stiction*;
- viscous friction and
- Coulomb friction.

The total friction force can be calculated as follows:

$$F_{friction}(v) = \left[F_c + (F_s - F_c)\,e^{-(v/v_s)^2}\right]\mathrm{sgn}(v) + F_v \times v, \quad (2)$$

where $F_c$ is the Coulomb friction coefficient, $F_s$ is the static friction coefficient, $v$ is the stem velocity, $v_s$ is the Stribeck velocity and $F_v$ is the viscous friction coefficient.