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An online tuned novel nonlinear PI controller for stiction compensation in pneumatic control valves

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ABSTRACT

A novel Nonlinear PI Controller (NPIC) has been proposed for effective control of flow process employing a sticky pneumatic control valve. The proposed control scheme has been inherited from a classical PI control structure with a difference that the integral gain has been varied in accordance with the instantaneous error and the rate of change of error. The tuning of controller has been carried out online using Differential Evolution algorithm. To evaluate the effectiveness of the proposed controller, a comparative study with the conventional PI controller has also been carried out for the setpoint tracking, disturbance rejection and robustness to parameter uncertainties on account of operating point change on a laboratory scale nonlinear flow process. Based on these intensive experimental evidences, it has been concluded that the NPIC performed far better than the conventional PI controller for all the case studies and suppressed effectively any stiction induced oscillations.

1. Introduction

Pneumatic control valves are ubiquitous in industries such as distillation industries, pulp and paper industries, pharmaceutical industries, power generation industry etc. The use of a pneumatic control valve is generally for the manipulation of the flow rate. Generally, it is assumed that a pneumatic control valve provides linear operation i.e. one to one relationship between the stem position and the flow rate. In a real world scenario, this assumption can cause serious deteriorating implications and most of the inherent nonlinearities in the final control elements should not be neglected if not compensated at all. One of the most common nonlinearities in pneumatic control valve is '*stiction*' which may become a major source for the reduced level of plant productivity. Stiction can cause oscillation in a control loop of a plant and it may further cause plant wide oscillations which in turn may degrade product quality, e.g. the composition of a product drawn from a distillation column can oscillate and may be different from what the desired. The term stiction is an amalgamation of two words i.e. 'static' and 'friction' and various definitions have been presented over the years to define the exact notion of this term. A very simple and informative definition has been presented by Choudhury et al. in 2005, as "*Stiction is a property of an element such that its movement in response to a varying input is preceded by a static part (deadband plus stickband) followed by a sudden abrupt jump called slip-jump. Its origin in a mechanical system is static friction which exceeds the friction during smooth movement*" [1].

This nonlinear behavior in pneumatic control valves due to stiction closely resembles with the backlash nonlinearity, commonly found in mechanical gearing arrangements. The effect of the stiction on the input–output relationship of a pneumatic control valve can be well understood with the help of Fig. 1. From the shown characteristics it can be clearly inferred that the movement of stem cannot be reversed until a specific minimum input change, equal to "deadband (D) plus stick band (J)", denoted as stiction band (S) in Fig. 1, is not achieved. Another feature of this characteristic is "stick-slip" phenomena, also known as slip-jump behavior. This stick slip behavior occurs whenever stem becomes stationary and valve input changes in such a way so as to move stem in the same direction. Since static friction is always greater than dynamic friction, larger force is required to move stem from steady position than the force required by stem in moving condition. As soon as the valve input surpasses 'S', the energy stored in actuator forces the stem to move abruptly and thereafter smoothly until the valve sticks again [2].

Generally, the value of 'S' is assumed to be same in both directions of stem travel while practically this is not the case and the value of 'S' differs for both directions. As a result there are different values of 'S' for the upward and downward movement of stem and the valve characteristic shown in Fig. 1 is not general. In addition to the above the value of 'S' also depends upon the stem

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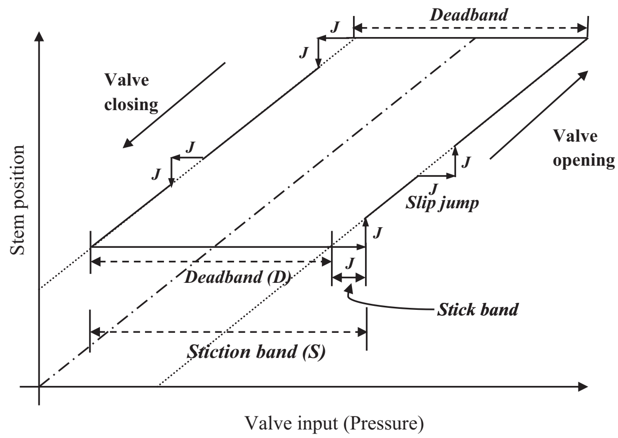

Fig. 1. Typical input–output characteristic of an air-to-open pneumatic control valve with stiction.

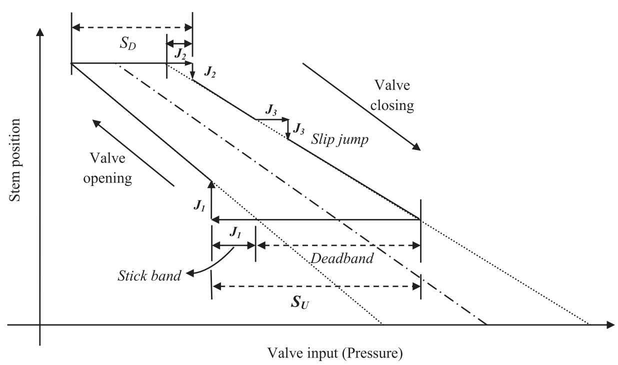

Fig. 2. Generalized input–output characteristic of an air-to-close pneumatic control valve with stiction.

position and hence the valve characteristics become too complex as it includes the direction dependency along with the position dependency. A more realistic representation of the valve characteristic can be shown as in Fig. 2. As shown in this figure, the value of '*S*' depends upon the instantaneous position of stem and varies for whole operating range. This variation of '*S*' poses a very critical problem in quantification of plant parameters and thereby modeling of the valve characteristic becomes very tedious. In Fig. 2, S_U shows the stiction band value when the stem is going upwards (valve is opening) and S_D shows the stiction band value when stem is moving downwards (valve is closing).

Since stiction is a major cause for reduction in plant efficiency, researchers in the last decade have given a proper attention to this problem. The most common research trend in this area is focussed on a data driven modeling of pneumatic control valve with stiction [1], stiction compensation through additional compensator along with the controller [3–5], and compensation techniques without additional compensator [6,7] etc. The research work in this field can also be linked to a broader area of study, termed as 'tribology' which deals with friction, lubrication, or in other words deals with the science of interacting surfaces in relative motion. The researchers having interest in tribology are more inclined towards the studies of friction in machines and strive for reducing the negative effects of friction. Armstrong-Hèlouvry et al. (1994) presented a very good survey on modeling, analysis and compensation methods for friction in machines. A broad range of fields including tribology, lubrication, physics and control were covered in his survey paper. Some of the several compensation techniques to overcome stiction in machines were discussed such as stiff proportional derivative (PD) control, PD with integral control with deadband, dithering and impulsive control techniques [8]. A survey by Rinehart (1997) reported that nearly 80% of the control valves, used in the industry, were not adhered to the dynamic performance standards. This included improper sizing and other valve nonlinearities such as stiction [9]. In view of this hidden menace, '*stiction*', various methods have also been proposed in recent past for its compensation. The most common and the obvious remedy, which can be adopted, is proper maintenance of the control valves. Proper maintenance of the valves may reduce stiction severity and thus performance of the associated control loops can be improved [10]. The maintenance work is usually performed during production stops, typically, at an interval of 6 months to 3 years. The time duration between two consecutive plant shutdown is quite long and losses incurred in this period can also be very high and are undesirable [5]. Further, dithering and impulsive control techniques which make use of high frequency pulses were also proposed to overcome stiction. These pulses are added to controller output but are generally filtered out by the typical low pass characteristic of pneumatic actuators hence making these techniques ineffective in pneumatic control valve [5]. Kayihan and Doyle (2000) suggested that the positioners in a pneumatic control valve can be replaced by a linear PI control scheme [11]. Their approach was to control the stem position by using a local nonlinear controller using input–output linearization with internal model control. The problem with this approach was that its performance was majorly dependent upon the input–output linearization control law which needed the exact information about the valve which is quite hard to know in a large scale industry. Gerry and Ruel (2001) presented some online measures to detect and quantify stiction. For the detection and quantification, they recommended varying controller output in small steps until a change in process variable (*PV*) is detected, the increment in controller output was assumed to be as a measure of stiction, as soon as a change in *PV* appears [6]. For the stiction compensation purpose, they proposed use of PI controller with bandgap; adjustment of the positioner parameters, if installed; replacement of integral control from PI controller with proportional control using high proportional gain etc. But these methods may not serve as an efficient way to compensate stiction in a large scale plant since making changes to a huge number of pneumatic control valves installed in the plant is quite cumbersome and tedious task.

Hägglund (2002) proposed a "Knocker Method" for the stiction compensation which uses short pulses with variable width and amplitude. The parameters of the knocker pulse were defined by the status of control action. These short pulses were further added to the control signal to compensate for the stiction in pneumatic control valves [3]. However to ensure efficient implementation of the knocker method, tuning of the amplitude, pulse width, and time between each pulse is quite essential. Though methods are available to automate the process of application of knocker pulse and the *PV* variability was reduced to six to seven times but on the expense of increased stem movement which is not desired in order to avoid valve damage due to wear and tear [4]. Srinivasan and Rengaswamy (2008) presented an efficient stiction compensation technique "two move approach" which used a separate compensator [5]. The output of the compensator at each instant was derived on the basis of instantaneous value of controller output (*OP*), derivative of controller output and the '*S*'. Thus compensation scheme was highly dependent on exact measurement of stiction measure. It was also assumed that there is no mismatch between plant and its mathematical model, which cannot be guaranteed in a real world scenario. Farenzena and Trierweiler (2010) presented a modification to the existing "two move approach". They claimed that the proposed method could yield a faster closed loop performance than the open loop process and was able to handle disturbance and setpoint change on the