

Chapter 2

Stiction Modelling

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Pneumatic control valves are widely used in the process industry. Two types of valve-stiction models have been proposed in the literature. One is a detailed physical model that formulates the stiction phenomenon as precisely as possible. The other is a data-driven model that describes the relationship between the controller output and the valve position. Since a detailed physical model has a number of unknown physical parameters, it is time consuming as well as difficult to simulate an actual control valve using such a model. The value of a physics-based model is that it gives insights into the phenomena that are observed in practice and indicates which effects must be captured in a data-driven model. A data-driven model, on the other hand, is useful because it has only a few parameters and these are easy to define and simple to understand. This chapter briefly discusses a physics-based valve model followed by a detailed description of data-driven stiction models.

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2.1 Introduction

One important moving part in a feedback control loop is the control valve. If the control valve contains non-linearities, *e.g.* stiction, backlash, and deadband, the valve output may be oscillatory that in turn can cause oscillations in the process output. Among the many types of non-linearities in control valves, stiction is the most common and is one of the long-standing problems in the process industry. It hinders the achievement of good performance of control valves as well as control loops. Many studies [5, 35, 48, 51, 52, 63, 83, 100, 108, 121, 132] have been conducted to define and detect static friction or stiction. Choudhury *et al.* [15] proposed a formal definition of stiction and developed a data-driven stiction model. This chapter addresses the issue of modelling valve friction or stiction. Simulation using a physics-based model gives fundamental insights into the effects of friction on a control loop containing a sticking valve. The disadvantage of a physics-based model is that it requires a knowledge of quantities such as the mass of the moving parts and the friction forces that makes it infeasible for industrial studies or span of the valve input signal.

In industrial practice, stiction and other related problems are identified in terms of the percentage of the valve travel or span of the valve input signal. The relationship between the magnitudes of the parameters of a physical model and stiction expressed as a percentage of the span of the input signal is also not known explicitly. On the other hand, a data-driven model is useful because it needs only a few parameters to be specified, which are easy to define in terms of the percentage of valve travel and span of the input signal, and simple to comprehend.

2.2 Physics-based Stiction Modelling

The general structure of a pneumatic control valve is shown in Fig. 2.1. This valve is closed by a spring elastic force and opened by air pressure. Flow rate is changed according to the plug position, which is determined by the balance between the spring force and the force on the diaphragm due to air pressure. The plug is connected to the valve stem. The stem is moved against the static or kinetic frictional force caused by packing, which is a sealing device to prevent leakage of process fluid. Smooth movement of the stem is impeded by excessive static friction. The valve position cannot be changed until the controller output overcomes this static friction, and the stem may slip and jump when the static friction is overcome. Once the valve is moving, the movement of the stem is affected by dynamic friction that is generally less than the static friction, and after an initial jump the movement proceeds smoothly. The movement stops when the elastic force of the spring and the force due to friction exactly balance the force due to air pressure.

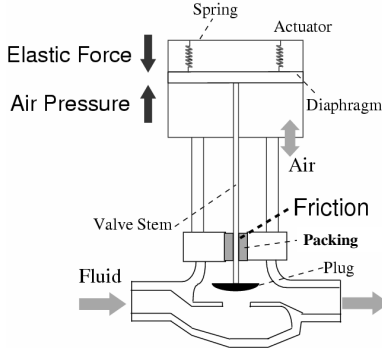


Fig. 2.1 Structure of pneumatic control valve

For a pneumatic sliding stem valve, the force-balance equation based on Newton's second law can be written as:

$$M \frac{d^2x}{dt^2} = \sum \text{Forces} = F_a + F_r + F_f + F_p + F_i, \quad (2.1)$$

where M is the mass of the moving parts, x is the relative stem position, $F_a = Au$ is the force applied by pneumatic actuator, where A is the area of the diaphragm and u is the actuator air pressure or the valve input signal, $F_r = -kx$ is the spring force, where k is the spring constant, $F_p = -A_p \Delta p$ is the force due to fluid pressure drop, where A_p is the plug unbalance area and Δp is the fluid pressure drop across the valve, F_i is the extra force required to force the valve to be into the seat and F_f is the friction force [30, 68, 131]. Following Kayihan and Doyle III [68], F_i and F_p will be assumed to be zero because of their negligible contribution to the model. The friction force (F_f) includes static and moving friction. The expression for the moving friction is in the first line of Eq. 2.2 and comprises a velocity independent term F_c known as Coulomb friction and a viscous friction term vF_v that depends linearly upon the velocity. Both act in opposition to the velocity, as shown by the negative signs:

$$F_f = \begin{cases} -F_c \text{sign}(v) - vF_v & \text{if } v \neq 0 \\ -(F_a + F_r) & \text{if } v = 0 \text{ and } |F_a + F_r| \leq F_s \\ -F_s \text{sign}(F_a + F_r) & \text{if } v = 0 \text{ and } |F_a + F_r| > F_s \end{cases}. \quad (2.2)$$

The second line in Eq. 2.2 is the case when the valve is stuck. F_s is the maximum static friction. The velocity of the stuck valve is zero, therefore the acceleration is zero also. Thus, the right-hand side of Newton's law is zero, such that $F_f = -(F_a + F_r)$. The third line of the model represents the situation at the instant of breakaway. At that instant the sum of forces is $(F_a + F_r) - F_s \text{sign}(F_a + F_r)$, which is not zero if $|F_a + F_r| > F_s$. Therefore, the acceleration becomes non-zero and the valve starts to move.

Many refinements exist for this friction model including the Stribeck effect that gives a detailed treatment of the static friction spike between F_c and F_s , and variable breakaway forces such that the value of F_s depends on how long the valve has been stuck. The classic friction model presented here is sufficient to capture major features and can model deadband and stick-slip effects. In order to use the physical model of valve stiction, knowledge of several parameters such as M , F_s , F_c and F_v , is required. Explicit values of these parameters depend on the size and manufacturer of the valve and are difficult to obtain in practice. Therefore, physical models of valve friction are not easily available for routine use. The alternative choice is to use a data-driven stiction model, which is relatively simple and easy to understand and use in simulation.

2.3 Data-driven Stiction Modelling

Two main classes of data-driven stiction models have appeared in the literature – they are termed one-parameter and two-parameter models.

2.3.1 One-parameter Stiction Model

Stenman *et al.* [117] reported a one-parameter data-driven stiction model. The model is described as follows:

$$y(k) = \begin{cases} u(k-1) & \text{if } |u(k) - y(k-1)| < d \\ u(k) & \text{otherwise} \end{cases}, \quad (2.3)$$

where, u and y are the valve input and output, respectively, d is the valve-stiction band. The model compares the difference between the current input to the valve and the previous output of the valve with the deadband; see Eq. 2.3. However, the deadband (d) should be compared with the cumulative increment of the input signal since the valve became stuck. The one-parameter model is also not adequate as a dynamic data-driven model of valve stiction as explained in more detail in Choudhury *et al.* [21].

2.3.2 Two-parameter Stiction Model

For a dynamic stiction model, the challenges are (i) to model the tendency of the valve to stay moving once it has started until the input changes direction or the velocity goes to zero, and (ii) to include the effects of deadband and the slip jump. This section describes two-parameter stiction models that can meet these challenges. The two-parameter stiction model first appeared in Choudhury *et al.* [13]. Parameters of

this valve-stiction model can be related directly to plant data and, furthermore, such a model produces the same open-loop and closed-loop behaviour as the physical model. The model only requires the controller output signal and the specification of deadband plus stickband (S) and slip jump (J), as shown and explained in Sect. 1.4 (Fig. 1.5). It overcomes the main disadvantages of physical modelling of a control valve; namely it does not require knowledge of the mass of the moving parts of the actuator, spring constant, and the friction forces.

2.3.3 Choudhury's Stiction Model

2.3.3.1 Model Formulation

The valve sticks only when it is at rest or changing direction. When the valve changes its direction it comes to a rest momentarily. Also, when the velocity of the valve is very small, the valve may stick. Once the valve overcomes stiction, it starts moving and may keep moving for some time, depending on the valve input and the amount of stiction present in the valve. In the moving phase (Fig. 1.5), the valve suffers only from dynamic friction, which is usually smaller than static friction. It continues to move until its velocity is again very close to zero or it changes its direction.

In the process industry, stiction is generally measured as a percentage of the valve travel or the span of the control signal [35]. For example, 2% stiction means that when the valve gets stuck, it will start moving only after the cumulative change of its control signal is greater than or equal to 2%. If the range of the control signal is from 4 to 20 mA, then a 2% stiction means that a change of the control signal less than 0.32 mA in magnitude will not be able to move the valve.

In the modelling approach described herein, it is assumed that the controller has a filter to remove the high-frequency noise from the signal. Section 2.3.3.2 gives more discussion on this topic. Then, the control signal is translated to the percentage of valve travel with the help of a linear look-up table. The model consists of two parameters – namely the size of deadband plus stickband S (specified in the input axis) and slip jump J (specified on the output axis). Figure 2.2 summarises the model algorithm, which can be described as:

- First, the controller output (mA) is converted to valve travel percentage using a look-up table.
- If the transformed controller output signal expressed as a percentage is less than 0 or more than 100, the valve is saturated (*i.e.* fully closed or fully open).
- If the signal is within the 0 to 100% range, the algorithm calculates the slope of the controller output signal.
- Next, the change of the direction of the slope of the input signal is taken into consideration. If the *sign* of the slope changes or remains zero for two consecutive instants, the valve is assumed to be stuck and does not move. The *sign* function of the slope gives the following outputs:

- If the slope of the input signal is positive, the $sign(slope)$ returns +1.
- If the slope of the input signal is negative, the $sign(slope)$ returns -1.
- If the slope of the input signal is zero, the $sign(slope)$ returns 0.

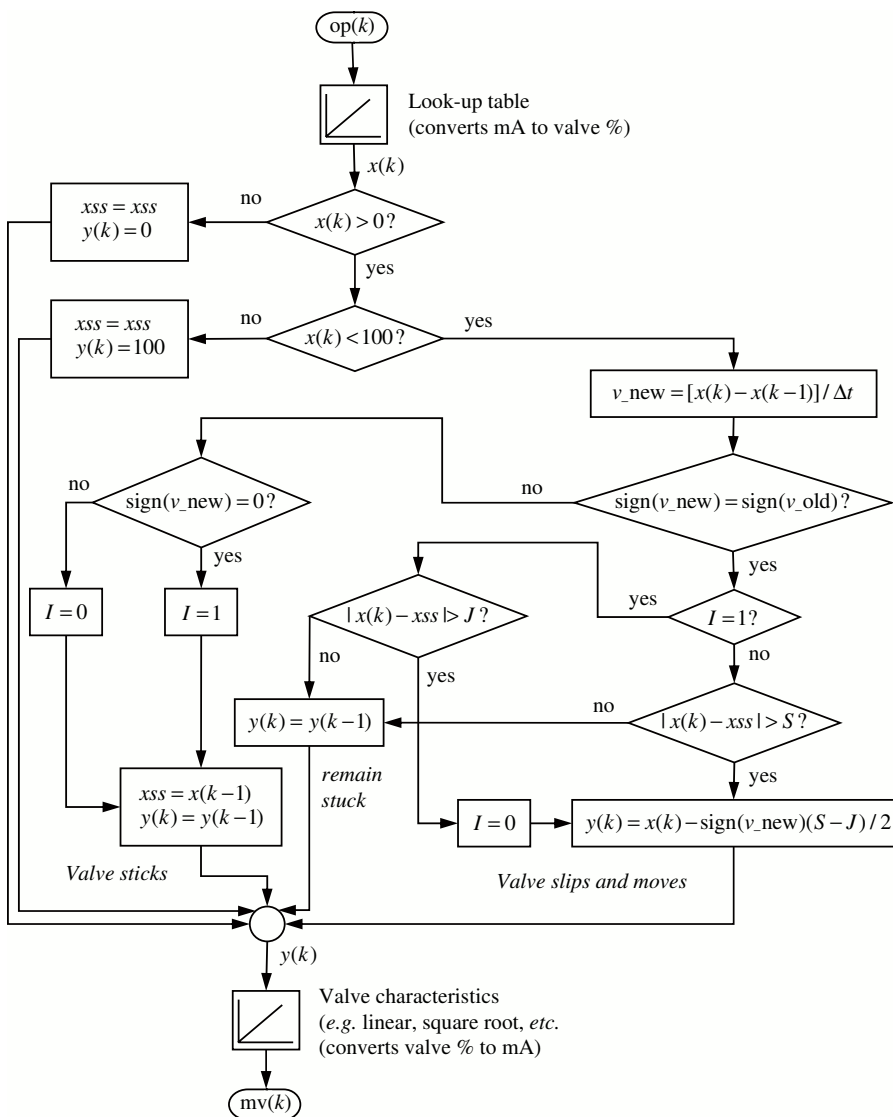


Fig. 2.2 Signal and logic flow chart of the two-parameter data-driven Choudhury's stiction model

Therefore, when $sign(slope)$ changes from +1 to -1 or *vice versa*, this means that the direction of the input signal has changed and the valve is at the beginning

of its stick position (points M and G in Fig. 1.5). The algorithm detects the stick position of the valve at this point. Now, the valve may stick again while travelling in the same direction (opening or closing direction) only if the input signal to the valve does not change or remains constant for two consecutive instants, which is uncommon in practice. For this situation, the $sign(slope)$ changes to 0 from +1 or -1 and *vice versa*. The algorithm again detects the stick position of the valve in the moving phase and this stuck condition is denoted with the indicator variable $I = 1$. The value of the input signal when the valve gets stuck is denoted as xss . This value of xss is kept constant and does not change until the valve gets stuck again. The cumulative change of input signal to the model is calculated from the deviation of the input signal from xss . It is noteworthy that this can also be performed by using a velocity threshold below which the valve will come to a rest or stop.

- For the case where the input signal changes direction (*i.e.* the $sign(slope)$ changes from +1 to -1 or *vice versa*), if the cumulative change of the input signal is more than the amount of the deadband plus stickband (S), then the valve slips and starts moving.
- For the case when the input signal does not change direction (*i.e.* the $sign(slope)$ changes from +1 or -1 to zero, or *vice versa*), if the cumulative change of the input signal is more than the amount of the stickband (J), then the valve slips and starts moving. This takes care of the case when the valve sticks again while travelling in the same direction [27].
- The output is calculated using the equation:

$$output = input - sign(slope)(S - J)/2 \quad (2.4)$$

and depends on the type of stiction present in the valve. It can be described as follows:

- Deadband: if $J = 0$, then it represents the pure deadband case without any slip jump.
- Stiction (undershoot): if $J < S$, then the valve output can never reach the valve input. There is always some offset or deviation between the valve input and the valve output. This represents the undershoot case of stiction.
- Stiction (no offset): if $J = S$, the algorithm produces pure stick-slip behaviour. There is no offset between the valve input and the valve output. Once the valve overcomes stiction, the valve output tracks or reaches the valve input exactly. This is the well-known *stick-slip case*.
- Stiction (overshoot): if $J > S$, the valve output overshoots the valve input due to excessive stiction. This is termed the overshoot case of stiction.
- The parameter J is an output quantity measured on the vertical axis. It signifies the slip-jump start of the control valve immediately after it overcomes the deadband plus stickband. It accounts for the offset or deviation between the valve input and output signals.

- Finally, the output is converted back to a mA signal using a look-up table based on characteristics of the valve such as linear, equal percentage or square root, and the new valve position is reported.

2.3.3.2 Dealing with Stochastic or Noisy Control Signals

The two-parameter stiction model uses the *sign* function to detect the change of valve direction. In the case of a noisy signal, this may cause numerical problems in the simulation. In real life, a noisy control signal causes the valve unnecessary movements and rapid wear and tear. In order to handle a noisy or stochastic control signal in simulation, a time-domain filter, *e.g.* an exponentially weighted moving average (EWMA) filter, can be used right after the controller to filter the noise. The work presented in this chapter uses the following filter:

$$G_f(z) = \frac{\lambda z}{z - (1 - \lambda)}. \quad (2.5)$$

The magnitude of λ will depend on the extent of noise used in the simulation. A typical value of λ can be chosen as 0.1.

2.3.4 Simulation of the Stiction Model

The two-parameter data-driven stiction model has been thoroughly examined using both open-loop and closed-loop simulation in [15,21]. Closed-loop behaviour of the two-parameter stiction model using a concentration control loop is presented here. The concentration loop has slow dynamics with a large dead time. The transfer function, controller and parameters used in simulation are shown in Table 2.1. The magnitudes of S and J are specified as a percentage of valve input span and output span, respectively.

Table 2.1 Process models, controllers, and stiction model parameters

Loop	Process	Controller	Stiction							
			Deadband		Undershoot		No offset Overshoot			
			S	J	S	J	S	J	S	J
Concentration	$\frac{3e^{-10s}}{10s+1}$	$0.2(\frac{10s+1}{10s})$	5	0	5	2	5	5	5	7

The transfer-function model for the concentration loop was adopted from Horch and Isaksson [51]. This transfer function with a PI controller in a feedback closed-loop configuration is used here for simulation. Simulation results for different stiction cases are presented in Figs. 2.3a and b. In both figures, thin lines are the controller output and thick lines are the process output. If an integrator is not present in

the process, the triangular shape of the time trend of the controller output is one of the characteristics of stiction [48]. If it is an integrating process with a PI-controller, the valve signal is integrated twice and appears as a series of parabolic segments.

Figure 2.3a shows the controller output (OP) and valve position (MV). Mapping of MV–OP clearly shows the stiction phenomena in the valve. It is common practice to use a mapping of PV–OP for valve diagnosis; see Fig. 2.3. However, in this case such a mapping only shows elliptical trajectories with sharp turn-around points. The reason for the latter is that the PV–OP map captures not only the non-linear valve characteristic but also the dynamics of the process. Therefore, if the valve position data are available, one should plot valve position (MV) against the controller output (OP) to diagnose a valve problem. Except in cases of liquid flow loops where the flow through the valve (PV) can be taken to be proportional to valve opening (MV), the PV–OP maps should be used with caution for stiction diagnosis.

2.3.5 Kano's Stiction Model

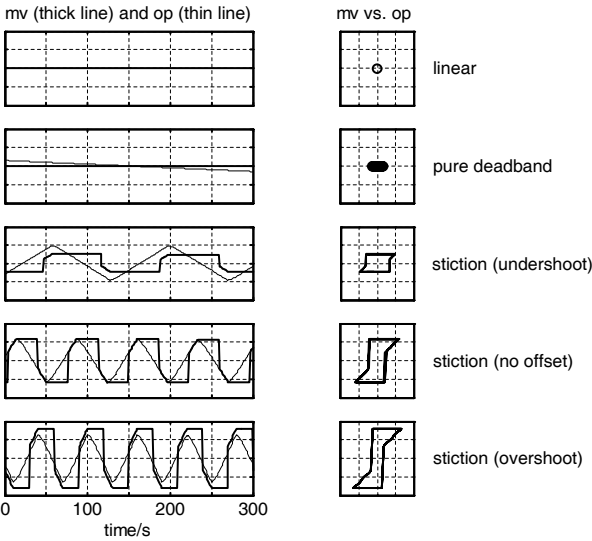
The two-parameter model as discussed in [13, 15] has been modified by Kano *et al.* [63] attempted to relate S and J to the elastic force, air pressure and frictional force. In Kano's model, S corresponds to the summation of static and dynamic friction and J corresponds to the difference between the static and dynamic friction; see Eq. 1.1. Having this in mind, they offered an alternative flow chart for simulating stiction. The flowchart for stiction simulation is presented in Fig. 2.4.

The input and output of this valve-stiction model are the controller output u and the valve position y , respectively. Here, the controller output is transformed to the range corresponding to the valve position in advance.

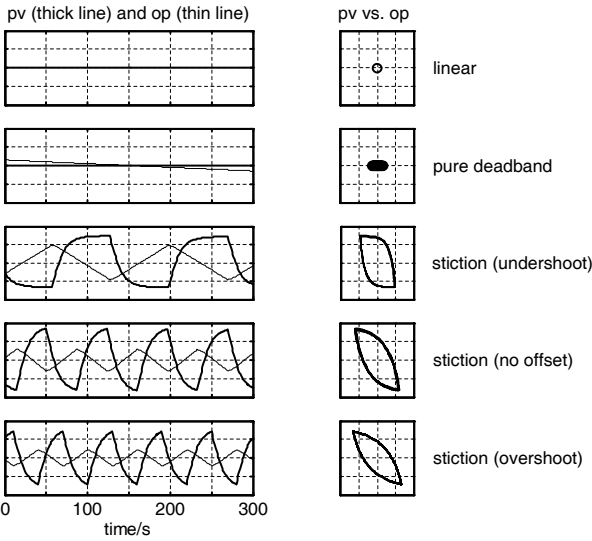
The first two branches in the flowchart check if the upper and the lower bounds of the controller output are satisfied. In Kano's model, two states of the valve are explicitly distinguished, denoted by the variable stp . In the moving state stp has the value 0, while in the resting state stp is 1. In addition, the controller output at the moment the valve state changes from moving to resting is defined as u_S . u_S is updated and the state is changed to the resting state ($stp = 1$) only when the valve stops or changes its direction ($\Delta u(t) - \Delta u(t-1) \leq 0$) while its state is moving ($stp = 0$). Then, the following two conditions concerning the difference between $u(t)$ and u_S are checked unless the valve is in a moving state. The first condition judges whether the valve changes its direction and overcomes the maximum static friction (corresponding to points C and F in Fig. 1.5). Here, $d = \pm 1$ denotes the direction of frictional force. The second condition judges whether the valve moves in the similar direction and overcomes friction. If one of these two conditions is satisfied or the valve is in a moving state, the valve position is updated via the following equation:

$$y(t) = u(t) - df_d = u(t) - \frac{d(S-J)}{2}. \quad (2.6)$$

On the other hand, the valve position is unchanged if the valve remains in a resting state.



(a)



(b)

Fig. 2.3 Closed-loop simulation results of a concentration loop using the data-driven stiction model: a) time trends of MV and OP (*left*), MV–OP mappings (*right*); b) time trends of PV and OP (*left*), PV–OP mappings (*right*)

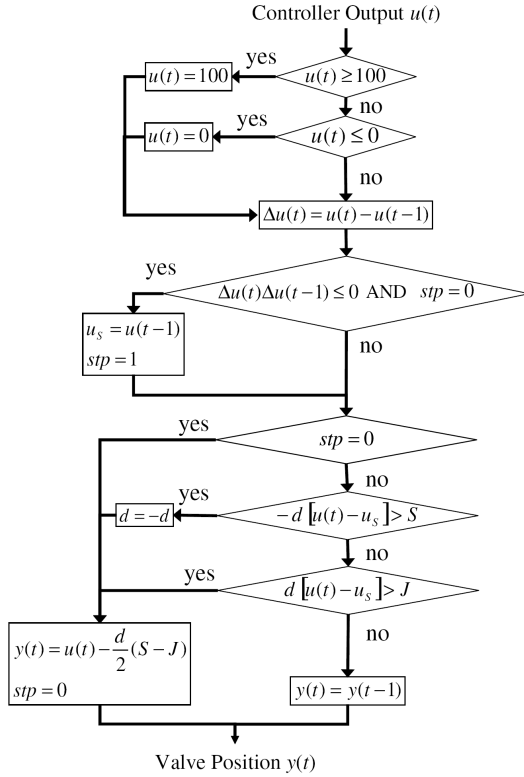


Fig. 2.4 Flow chart of Kano's valve-stiction model

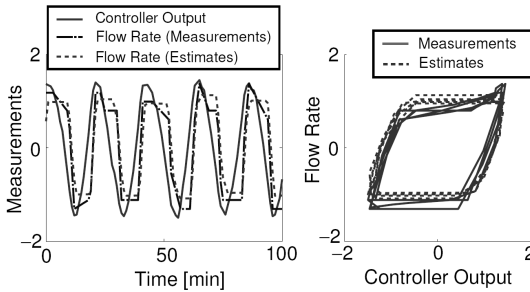


Fig. 2.5 Comparison between flow-rate measurements and estimates for validating valve-stiction model

To demonstrate the validity of this stiction model, simulation results are compared with operation data of a chemical process that suffers from valve stiction. The flow rate is estimated by calculating the valve position from the controller output with the stiction model and by assuming that the dynamics between the valve position and the flow rate is given by a first-order model:

$$P_F(t) = \frac{1}{0.2s + 1}. \quad (2.7)$$

Measurements and estimates of the flow rate are shown together with the controller output in Fig. 2.5. The flow-rate measurements proved coincident with that estimated by the stiction model.

The valve-stiction model developed here is based on the balance among the elastic force, the air pressure, and the frictional force, and it can describe the behaviour of pneumatic control valves with only two parameters S and J . For example, an ideal situation exists when $S = J = 0$ and no slip jump when $J = 0$.

2.4 Comparison Between Choudhury's and Kano's Stiction Models

2.4.1 Similarities

- Both models use the same parameters, S and J .
- Both models can produce the stiction behaviour of a control valve both when the valve sticks during the change in travel direction and when the valve sticks while travelling in the same direction.

2.4.2 Differences

- To detect when the valve sticks, Choudhury's model uses the sign function while Kano's model uses the product of the incremental valve input change.
- To deal with a stochastic control signal, Choudhury's model uses an EWMA, while Kano's model uses a first-order transfer-function model of the air chamber of the valve.

2.4.3 Comparisons Using an Industrial Example

This example compares the performance of both two-parameter data-driven stiction models described above. It is an industrial example that describes a level control loop that controls the level of condensate in the outlet of a turbine by manipulating the flow rate of the liquid condensate. In total, 8641 samples for each tag were collected at a sampling period of 5 s. Figure 2.6 shows a portion of the time-domain data. The left panel shows time trends for level (PV), the controller output (OP), which is also the valve demand, and valve position (MV), which can be taken to be the same as the condensate flow rate. The plots in the right panel show the char-

acteristics PV–OP and MV–OP plots. The bottom plot shows the presence of the stickband plus deadband and the slip jump. The slip jump is large and visible from the bottom plot, especially when the valve is moving in a downward direction. It is marked as “A” in the figure. It is evident from this figure that the valve output (MV) can never reach the valve demand (OP). This kind of stiction is termed as the *undershoot case* of valve stiction in this study. The PV–OP plot does not show the jump behaviour clearly. The slip jump is very difficult to observe in the PV–OP plot because the process dynamics (*i.e.* the transfer function between MV and PV) destroy the pattern.

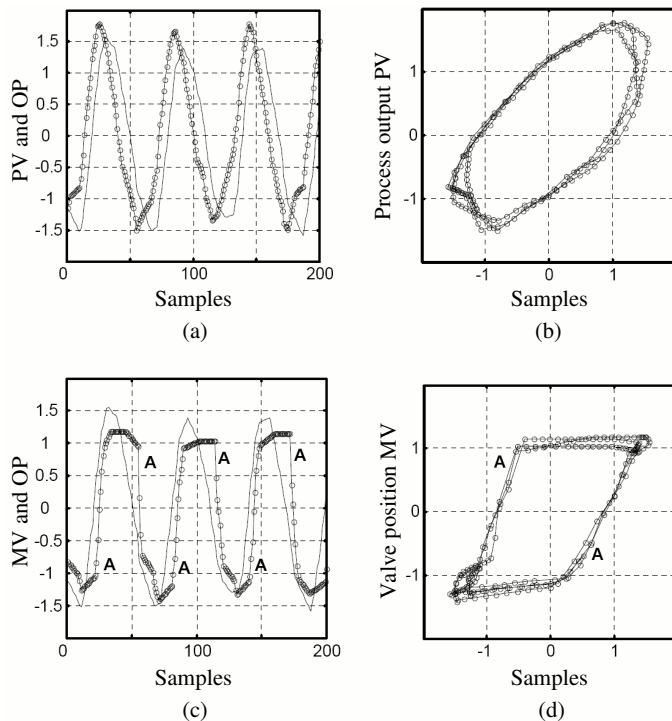


Fig. 2.6 Flow control cascaded to level control in an industrial setting: a) PV and OP trend (line with circles: PV, thin line: op); b) PV–OP plot; c) MV and OP trend (line with circles: MV, thin line: OP); d) MV–OP plot

The stiction models are tested by driving them with the controller output signal of the industrial control loop. When the stiction models are run, they generate a simulated manipulated variable that can be compared to the real manipulated variable captured from the plant. A close match would indicate that the stiction model has captured the dynamic stiction behaviour of the real valve. In Fig. 2.7, the output of the stiction models in response to the controller output signal of this data is compared with the actual valve position data to see how accurately the two-parameter

stiction models can reproduce the results. In this figure, only 500 samples are shown to ensure a better visibility of the trends. For both models $S = 10$ and $J = 3$ were used. The top panel shows the controller output signal. The middle panel compares the actual valve-positioner data with the predicted valve-positioner data using Choudhury's model while the bottom panel compares the actual valve-positioner data with the predicted valve-positioner data using Kano's model. For both cases, the mean-squares errors (MSE) are calculated using:

$$\text{MSE} = \frac{\sum_{i=1}^N (mv - mv_{\text{predicted}})^2}{N}, \quad (2.8)$$

where N is number of data points. In this case, $N = 8641$. For both models, the MSE is 0.93.

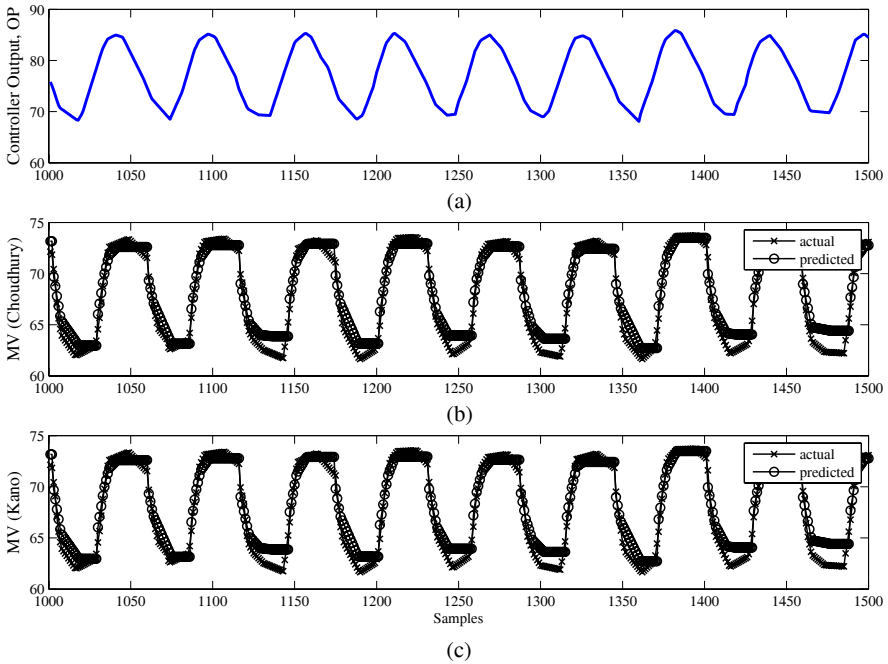


Fig. 2.7 Comparison of Choudhury's and Kano's stiction models using an industrial example (data samples 1001–1500): a) OP trend; b) MV trends (Choudhury's model); c) MV trends (Kano's model)

Figure 2.7 shows that both models can reproduce the stiction behaviour of a control valve successfully. However, it is interesting to observe the actual industrial valve moving around, while the model-predicted MV says it should be stuck. This is especially true in the valleys of the MV oscillation in the lower signal part. In the upper signal part, the industrial data also show valve sticking in some peaks; these

are marked with dashed ellipses in Fig. 2.8, which shows another data window. The shape of the industrial actual MV is somewhat different from that of the model-predicted MV. This means that the data-driven stiction model is failing to capture some of the physics. One possible reason is a more complicated friction behaviour. For instance, in addition to the static and dynamic friction, the friction in the moving phase may have regimes with different gradients in the velocity versus friction-force characteristic. Moreover, it seems that the valve shows some asymmetrical behaviour since it sometimes sticks in one direction but not in the other.

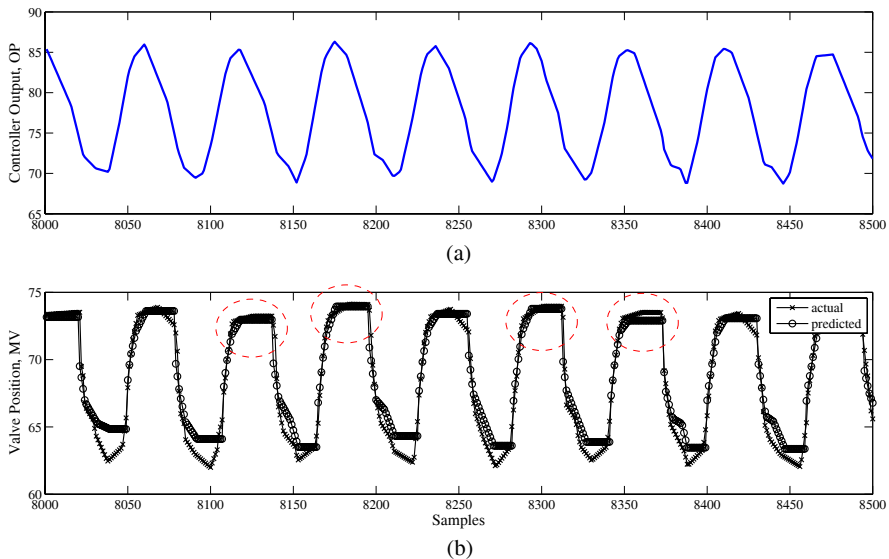


Fig. 2.8 Comparison of Choudhury's and Kano's stiction models using an industrial example (data samples 8001–8500): a) OP trend; b) MV trends

2.5 Summary and Conclusions

This chapter has described valve-stiction models. Both physics-based models and data-driven models are discussed. Although a physics-based model gives insights into the stiction phenomena that are observed in practice, it is difficult to use for simulation purposes because it is hard to determine the physical parameters, such as spring constant and static and dynamic friction forces. A data-driven model, on the other hand, is useful because it needs only a few parameters that are easy to define and simple to understand. At the same time, it can replicate the valve-stiction phenomenon quite successfully. Finally, both two-parameter stiction models as developed by Choudhury and Kano are compared using an industrial example. The validation test serves to show that both models are able to satisfactorily simulate the stiction effects.

Detection and Diagnosis of Stiction in Control Loops

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