Sensors & Transducers, Vol. 178, Issue 9, September 2014, pp. 250-255

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On-line Detection of the Change of Friction in Control Valve

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Received: 7 July 2014 /Accepted: 29 August 2014 /Published: 30 September 2014

Abstract: The function of stuffing box in pneumatic control valve is dynamic seal, but it also produces friction. The friction will affect the performance of position control. This paper proposes a method, based on the error integral indexes of control loop. On-line detection of the change of friction in control valve can use this method. Firstly, we use TOPSIS method to choose the appropriate error integral index. And then using the appropriate index describes the change of friction. The results found that, the relevance between the change of friction in control valve and the error integral of control loop is existing. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Control valve, Friction, Error integral, On-line detection, TOPSIS.

1. Background

The function of stuffing box in pneumatic control valve is dynamic seal, at the same time the box produces friction between stem and packing. The control valve, as the only movement device in control loop, will appear stem wear, packing deformation or breakage. The main reasons causing them are medium impacting and the valve in the high temperature environment for a long time. These faults can lead to increase the friction between stem and packing. With the increase of friction, the valve will be stuck. Valve sticking can make the control loop produce oscillation phenomenon. So the research of the change of friction is not only important to control valve but also to control loop.

Under the condition of invariable control valve body, we can replace the different stuffing and compress the gland of stuffing box. Through these methods, the friction will change. What can account for change in the performance of control system. So we can assume that the change of friction is easy to obtain, through the research of control system's performance. Normally, the merits of the control system can be evaluated by the error integral indexes of control loop [1]. Because they can reflect the dynamic (overshoot, rise time and so on) and steady-state (settling time and steady-state error) performance of the control system. So we propose a method, based on the error integral indexes of control loop. On-line detection of the change of friction in control valve can use this method. The structure chart is shown in Fig. 1.

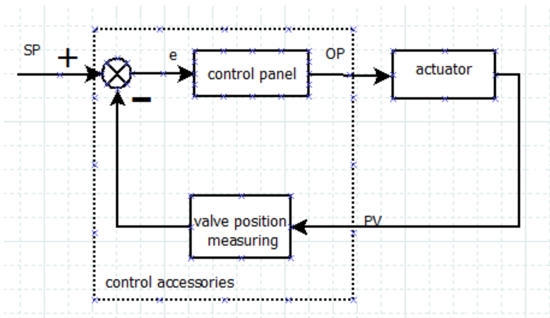

Fig. 1. The structure chart.

So this paper will focus on how to select the proper error integral index, and then explore the quantitative relationship between the friction and the proper one.

2. Friction Analysis for the Control Valve

According to the pneumatic signal, the pneumatic control valve adjusts the flow of medium. In this paper, a single-seat pneumatic diaphragm control valve has been analyzed. As formula 1 shows, the forces on the valve core and valve stem decide the position of the valve core.

$$\sum F = f_a + f_k + f_f + f_p \,, \tag{1}$$

where f_a represents the force on the film of air chamber. f_k represents the force on spring-stretch. The friction of valve stem, f_f, can be divided into static friction f_s and dynamic friction f_d. f_p represents the force on the valve core, caused by differential pressure on the valve. f_p can be ignored, because there is no medium through the valve. According to the friction model proposed by Stribeck [2], Choudhury [3], f_f will be as below.

$$f_f = \begin{cases} -f_c sign(v) - vf_v & if\ v \neq 0 \\ -(f_a + f_k) & if\ v = 0 and |f_a + f_k| \leq f_s \\ -f_s sign(f_a + f_k) & if\ v = 0 and |f_a + f_k| \geq f_s \end{cases} , \tag{2}$$

Coulomb friction, f_c is a constant force which acts in the opposite direction to motion and is independent of the magnitude of velocity. f_v represents viscous friction. It acts in the direction opposite to friction. f_s represents static friction. As formula 2 shows, when the control valve receives an incentive signal, the valve stem acts accordingly. Firstly, the valve stem should overcome the maximum static friction force, as shown in the third equation of formula 2. Then stem begins to move, sliding friction acts on the stem. The size of it is shown in the first equation. At last, the stem becomes still, static friction acts on the stem, size by the second equation.

3. Analyze the Error Integral of Control Loop, According to TOPSIS Method

3.1. The Error-integral of Control Loop

The pneumatic control valve can be regarded as a pure lag and one-order inertia system $ke^{-\tau s} / (Ts+1)$, when it is fail-safe. So we adopt the IMC - PID [10] control and use internal model method to adjust PID parameters. In the experiment, P=0.25, I=0.0625, D=0. These parameters make the performance of position control great. Eliminate the situation that, the control loop oscillates because of poor PID parameters. Only in this way can that, using the appropriate error integral describes the change of friction, be meaningful. There are five commonly used error integral indexes [4-7], as shown in Table 1.

Table 1. Five commonly used error integral indexes.

IE: integral error	$error = \int_{t=0}^{T} e(t)dt$
IAE: integral of absolute error	$error = \int_{t}^{T} \lvert e(t) \rvert dt$
ITAE: integral time absolute error	$error = \int_{t}^{T} t * \lvert e(t) \rvert dt$
ITE: integral time absolute error	$error = \int_{t=0}^{T} t * e(t)dt$
ISE: integral square error	$error = \int_{t=0}^{T} [e(t)]^2 dt$

3.2. TOPSIS Method

The full name of TOPSIS is' Technique for Order Preference by Similarity to Ideal Solution'. This method is put forward by Hwang and Yoon in 1981, which applies to identify solutions from a finite set of alternatives based upon simultaneous minimization of distance from an ideal point and maximization of distance from a nadir point. So the key to this method is determining the ideal and nadir values of the indexes.

The ideal value is the best solution. Every attribute values of it reached the best values. On the other hand, the nadir value is the worst solution. Then we should work out distances of each alternative to the ideal and nadir value. According to the distances, the proximity of each alternative to the ideal point will be confirmed [8, 9].

TOPSIS is the method, which has many advantages. For example, it can normalize the original data, what eliminates influence brought by different dimension. What's more, TOPSIS can make the best of original data. So it fully reflects the gap between each scheme. In today's society, TOPSIS is increasingly widely used.

Specific steps as shown below:

1. Establishing the initial matrix A, X_{ij} represent the elements in matrix A. i=1, 2, ... , m; j=1, 2, … , n

2. Normalizing the initial matrix, then we get matrix B. $X_{ij}{}'$ represent the elements in matrix B. i=1, 2, ..., m; j=1, 2, …, n

3. According to the characteristics of indicators, calculating the ideal and nadir value.

The ideal value:

$$f_j^* = \begin{cases} \max(f_{ij}),\, j \in J^* \\ \\ \min(f_{ij}),\, j \in J' \end{cases} \qquad j = 1, 2, \ldots, n$$

The nadir value:

$$f_j' = \begin{cases} \min(f_{ij}),\, j \in J^* \\ \\ \max(f_{ij}),\, j \in J' \end{cases} \qquad j = 1, 2, \ldots, n$$

J^* represents efficiency indicators, J' represents cost indicators. f_{ij} represents row vectors in the matrix B.

Working out distances of each alternative to the ideal and nadir value.

$$\begin{aligned} S_{ij}^* &= \sqrt{\sum_{j=1}^{m} (f_{ij} - f_j^*)^2},\, j = 1, 2, \ldots, n, \\ S_i' &= \sqrt{\sum_{j=1}^{m} (f_{ij} - f_j')^2},\, j = 1, 2, \ldots, n. \end{aligned} \quad , \qquad (3)$$

According to the distances, the proximity of each alternative to the ideal point will be confirmed.

$$C_i^* = S_i' / (S_{\mathrm{i}}^* + S_i'), i = 1, 2, \ldots, m., \qquad (4)$$

The optimal decision will be proposed, according to the size of proximity.

In this paper, we put five error integral indexes as solutions. At the same time, different torques will be indicators. But these indicators can’t be used as efficiency or cost indicators. When the torque is increasing, the friction will also increase. So we can see the vector of biggest change as ideal value, the vector of smallest change as nadir value. What are shown in formula 5, 6.

The ideal value:

$$\begin{aligned} &f_j^* = \left[\min(f_{i1}), \max(f_{i2}), \max(f_{i3})\right] \\ &i = 1, 2 \ldots, 5 \end{aligned} \quad , \qquad (5)$$

The nadir value:

$$\begin{aligned} &f_j' = \left[\max(f_{i1}), \min(f_{i2}), \min(f_{i3})\right] \\ &i = 1, 2 \ldots, 5 \end{aligned} \quad , \qquad (6)$$

According formula 3, 4, the proximity of each alternative to the ideal point will be confirmed. So the optimal decision will be proposed.

4. The Introduction of Experiments

4.1. The Principle of Experiments

Under the condition of invariable control valve body, we can replace the different stuffing and compress the gland of stuffing box. Through these methods, the friction will change. As everyone knows, the change of force will cause deformation of object. So we need to stick the strain gauge on the valve stem. The deformation signals of stem become electrical signals. So we can get the electrical signals by NI9219 DAQ Card. At last, the friction is obtained by LABVIEW software. We also can get input signals and output signals of the valve position through MATLAB software. So the change of friction, input signals and output signals of the valve position will be obtained at the same time. Experimental equipment is shown in Fig. 2.

1. Computer
2. NI9219 DAQ Card
3. Intelligent positioned (E/P+ Valve position feedback)
4. Homemade panel
5. Pneumatic control valve (produced by Zhe Jiang SanFang control valve limited liability company)

Fig. 2. Test platform.

4.2. Experimental Result

Through the module of serial communication in MATLAB software, giving an excitation signal to control panel. What makes the valve position change to 50 %. Then giving a 1.5 % step signal called SP, and receiving the valve position signal called PV. We can draw the curve from all signals, as shown in Fig. 3 (the stuffing is PTFE, the torque is 6 N·m).

Based on the definition of five kinds of error integral index, calculating each value IE=19.6, IAE=2600, ITAE=67400, ITE=828, ISE=3160.

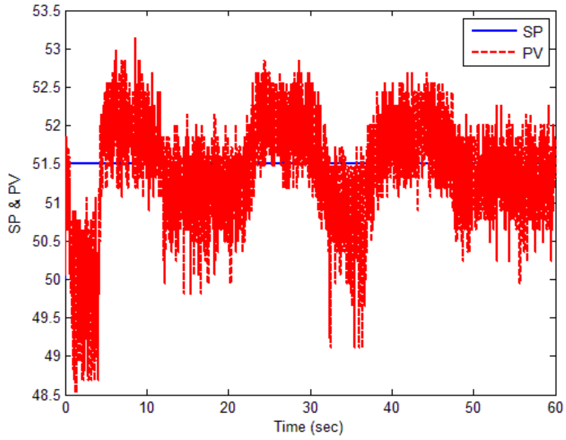

Fig. 3. The curve of SP and PV.

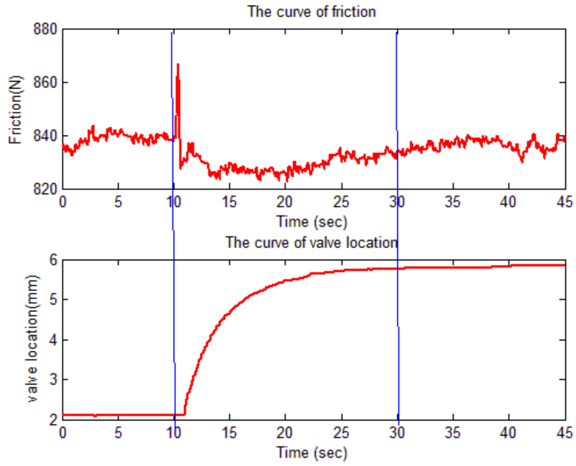

Fig. 4. The curve of friction.

In the same way, we can put all stuffingand torque together, as shown in Table 2.

Table 2. Experimental result.

Index /friction \ Torque (N·m)	Packing		
	Initial torque	**6**	**12**
IE	90.08	23.0	272
IAE	1370	980	1570
ITAE	21200	13200	26500
ITE	1010	800	1250
ISE	1140	1530	2460

Index /friction \ Torque (N·m)	Graphite		
	Initial torque	**6**	**12**
IE	45.2	-112	-201
IAE	4250	1510	2970
ITAE	64200	126000	196000
ITE	2470	-1820	-1520
ISE	2290	20400	25600

Index /friction \ Torque (N·m)	PTFE		
	Initial torque	**6**	**12**
IE	19.6	29.8	38.71
IAE	1970	2600	2660
ITAE	52000	67400	56700
ITE	919	828	3680
ISE	1870	3160	4110

Through NI9219 DAQ Card, the electrical signals caused by deformation of valve stem can be obtained. Then LABVIEW software calculates the friction. We can analyze an example, whose stuffing is PTFE and torque is 6 N·m. Then making a small step for control valve through control panel. The curve is shown in Fig. 4.

The figure is composed of two curves. The second curve is painted for valve position, which can reflect the response characteristics of the valve stem. The fist curve represents the friction of valve stem. So we can see that, when the control valve receives a step signal, the motion process of stem agrees well with theoretical predictions proposed by second section. The change of friction is that, from maximum static friction to dynamic friction to static friction. From this figure, we can clearly know the values of frictions.

Maximum static friction f_{ms}=868 N, dynamic friction f_d=830 N, static friction f_s=840 N.

In the same way, we can put all stuffing, torque and friction together, as shown in Table 3.

Table 3. The values of frictions.

Friction (N) \ Torque (N·m)	Packing		
	Initial torque	**6**	**12**
Maximum static friction	345	410	475
Dynamic friction	335	390	440
Static friction	341	399	450

Friction (N) \ Torque (N·m)	Graphite		
	Initial torque	**6**	**12**
Maximum static friction	780	1050	1225
Dynamic friction	770	970	1120
Static friction	775	975	1136

Friction (N) \ Torque (N·m)	PTFE		
	Initial torque	**6**	**12**
Maximum static friction	788	868	960
Dynamic friction	773	830	903
Static friction	780	840	912

5. The Analysis of Experimental Results

We can select an appropriate error integral index to describe the change of friction, according to TOPSIS method. And then analyze the situation that, the filler is packing, according to chart 2.

Firstly, listing the matrix A. We should reduce an order of magnitude for ITAE. Because it is bigger than others. At the same time, enlarge an order of magnitude for IE.

$$A = \begin{bmatrix} 900.8 & 230 & 2720 \\ 1370 & 980 & 1570 \\ 2120 & 1320 & 2650 \\ 1010 & 800 & 1250 \\ 1140 & 1530 & 2460 \end{bmatrix}$$

Then get matrix B:

$$B = \begin{bmatrix} 0.2922 & 0.0960 & 0.5495 \\ 0.4444 & 0.4092 & 0.3172 \\ 0.6877 & 0.5511 & 0.5354 \\ 0.3276 & 0.3340 & 0.2525 \\ 0.3698 & 0.6388 & 0.4970 \end{bmatrix}$$

Calculate the maximum and the minimum value:

$$f_j^* = \begin{bmatrix} 0.2922 & 0.6388 & 0.5495 \end{bmatrix}$$
$$f_j^{'} = \begin{bmatrix} 0.6877 & 0.0960 & 0.2525 \end{bmatrix}$$

According formula 3, 4, the proximity of each alternative to the ideal point will be confirmed. The proximities of IE, IAE, ITAE, ITE, ISE are 0.4768, 0.5272, 0.5693, 0.5027, 0.8781, respectively. The proximity of ISE is higher than others.

In the same way, we can obtain all the proximities with other stuffing, as shown in Table 4.

Table 4. The proximity of each alternative to the ideal point.

Stuffing / Indexes	Packing	Graphite	Ptfe
IE	0.4768	0.6902	0.4501
IAE	0.5272	0.4576	0.4901
ITAE	0.5693	0.1105	0.5499
ITE	0.5027	0.5733	0.5100
ISE	0.8781	0.7176	0.5871

From this chart, we can conclude that, the proximity of ISE is higher than others. So it is best to describe the change of friction. According to the chart 2 and 3, the friction becomes more and more large, as same as the values of ISE. So we can classify all values of ISE based on different kinds of friction, as shown in Fig. 5, Fig. 6 and Fig. 7. The Fig. 4 represents the relationship between maximum static friction and ISE in different kinds of stuffing. The Fig. 5 represents the relationship between dynamic friction and ISE in different kinds of stuffing. The Fig. 6 represents the relationship between static friction and ISE in different kinds of stuffing.

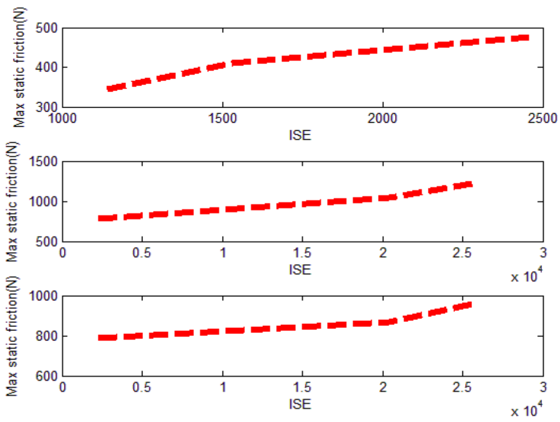

Fig. 5. The relationship between maximum static friction and ISE in different kinds of stuffing.

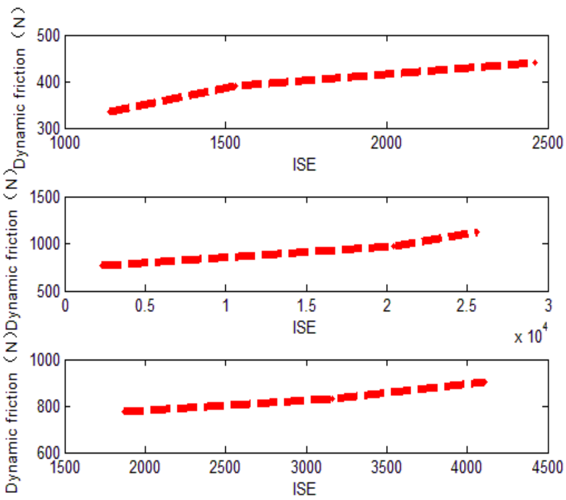

Fig. 6. The relationship between dynamic friction and ISE in different kinds of stuffing.

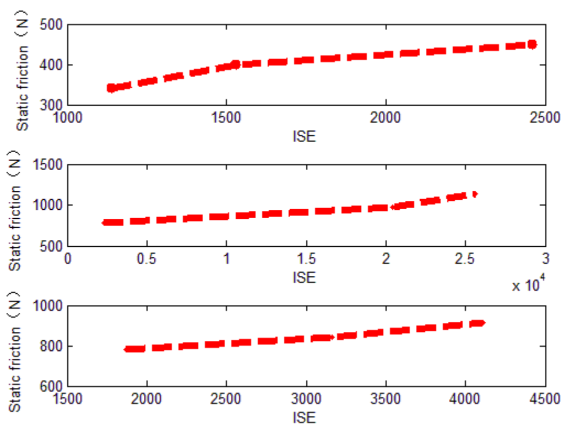

Fig. 7. The relationship between static friction and ISE in different kinds of stuffing.

The quantitative relationship between the friction and the ISE index is existing. That is $y = Ax + B$. y represents the value of friction; x represents the value of ISE. When the stuffing is different, the values of A and B will change.

According to these figures, we can see that each curve is made up of two similar slope straight lines: $y = ax + b$, $y = cx + d$. So the values of A and B are easily obtained: $A = \frac{a+b}{2}, B = \frac{c+d}{2}$. The quantitative relationships are shown in Table 5.

Table 5. The quantitative relationship between the friction and the ISE index.

x \ y	Packing		
	Maximum static friction	**Dynamic friction**	**Static friction**
ISE	y=0.12x +229	y=0.097x +241	y=0.01x +243

x \ y	Graphite		
	Maximum static friction	**Dynamic friction**	**Static friction**
ISE	y=0.024x +554.6	y=0.02x +563	y=0.02x +546

x \ y	PTFE		
	Maximum static friction	**Dynamic friction**	**Static friction**
ISE	y=0.079x +617	y=0.06x +639	y=0.02x +546

6. Conclusion

The experimental data is not enough because of the limited experimental conditions. So the quantitative relationship, between the friction and the ISE index, needs further exploration. But this paper proposes a new thinking for the on-line detection of the change of friction in control valve. When this method is applied to industry, it will greatly improve the efficiency of detection of the control valve and bring substantial profits for the enterprise.

Acknowledgements

The paper supported by National Natural Science Foundation of China, No. 61174108.

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