Sensors & Transducers, Vol. 177, Issue 8, August 2014, pp. 97-105

Sensors & Transducers

The Actuator Fault Diagnosis Based on the Valve Friction

Jiajiang Li, * Qunli Shang, Zheng Ding, Yayao Fang, Yang Liu
College of Information Engineering, Zhejiang University of Technology, Hangzhou, 310014, China
* Tel.: 13606709508
* E-mail: qlshang@zjut.edu.cn

Received: 18 June 2014 /Accepted: 31 July 2014 /Published: 31 August 2014

Abstract: Control valve (actuator) is the frequently moving terminal Instrument of the control system. To avoid the leaking of the actuator, there is packing at the moving parts. However, the friction caused by the packing can do harm to the control of the system. The washing effect of the media, high temperature, high pressure, frequent movement and other effects can result in the leaking of the packing and the deformation of the valve stem, which causes the change of the friction. The study of the control of the friction has always been an interesting topic in the industry. In this paper, we theoretically analyze the relationship of the friction of the packing and the static performance of the control valve, and offer a method to check the quality of the moving parts by attaching a strain gage (strain rosette) to the empty part of the valve stem. This method has been demonstrated via experiment and a method to do error detection is provided at last. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Control valve, Fault diagnosis, Static performance, Packing friction.

1. Introduction

To avoid the leaking of the fluid, packing is necessary at the joint parts of the actuator and the governing mechanism of the control valve. However, the packing can bring friction between the valve stem and the packing. Actuator(valve control), the only moving part of the control loop, can get larger friction because of the impact of the fluid, high temperature, abrasion of the valve stem and other effects, which results in the stiction of the control valve and the oscillation of the control loop. Therefore, it is important to study the change of the friction. The friction, as one part of the performance of the control valve, can be a good judgment to evaluate the performance of the whole control valve. The evaluation [1, 2] of the performance of the control valve is the evaluation of the whole control valve, including valve accessories. The evaluation of the performance of the control valve includes two parts: the static performance and the kinetic performance [3, 4]. The static performance is the static relation between the input signal and the stem displacement. It can check the moving performance, like the deviation between start and end point, rated stroke deviation, basic error, backlash, dead zone, reproducibility and linearity error and so on. The kinetic performance is the response time and the delay. In this paper, we theoretically analyze the relation of the friction of the packing and the static performance of the control valve, and offer a method to check the quality of the moving parts by attaching a strain gage (strain rosette) to the empty part of the valve stem. This method has been demonstrated via experiment and a method to do error detection is provided at last.

2. The Parameters of the Friction

In this section, we theoretically demonstrates the reason for setting these parameters, and take an inline check pneumatic sleeve control valve as an example to analyze the control valve stem force.

2.1. Friction Parameter

Control valve control performance is determined by the actuator, the valve positioner and the performance of the valve body. The performance of the actuator mainly depends on the performance of thrust movement. The control valve petitioner's main performance is based on the performance of valve position's control. And the main performances of the valve body is the ability of control the flow characteristics. Flow characteristics are mainly determined by the valve position control performance, reflected by F (the force works on the stem) and s (the stem displacement).When stem is in a steady state, the forces are balanced:

$$F_p(F_k) = F_f + F_k(F_p),$$

where F_p is the force produced by diaphragm pressure, F_f is the force produced by spring, and F_k is the packing friction.

From above formula, we need at least three sensors: pressure transmitter, valve positioner and strain gauge, where are used to measure the diaphragm pressure, displacement and packing friction separately.

As shown in Fig. 1, the main stem forces are the diaphragm pressure, the spring force and packing friction. The reason why the locations of the spring force and friction can exchange is that the final data depends on a steady state which processes an overshoot. The positive value or the negative value expresses the state of the stem, compression or tension, and it has nothing to do with the direction of friction.

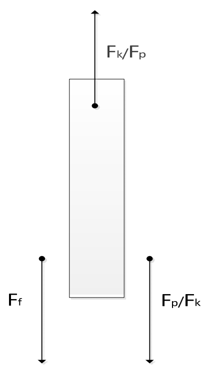


Fig. 1. The stem force analysis.

2.2. The Analysis of Friction Parameter

The reason to use the static friction performance parameters, further analysis of the above formula and the relationship between the static performances are shown as below:

1) The relationship between actuator and friction.

When The actuator static performances is stable, the relationship between the input signal and the displacement of the valve stem, the static performance and the spring rate, effective area of diaphragm, friction between stem and packing and so on follows the formula:

$$F_p = P_{\text{diaphragm}} \times S_{\text{effective area}},$$

where the effective area has something to do with the actuator characteristic. And there is also spring rate:

$$F_k = k \times \Delta x,$$

where k is the Spring rate; Δx is the Spring extension length;

2) The relationship between adjusting mechanism (valve positioner) and friction

The static steady-state performance of Regulating mechanism is the relationship between the control valve stem displacement and flow when it is stable.

The dynamic performance of Adjusting mechanism mainly influences dead zone.

Because the actuator and regulating mechanism is associated, actuators and regulating mechanism of partial performance cannot be subdivided, such as friction and dead zone.

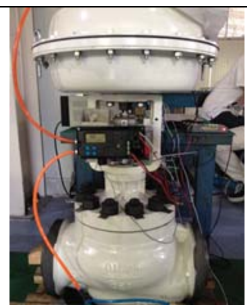
3. The Experimental Verification of Friction Parameters

This section verifies the theory with the experimental result.

3.1. The Introduction of Experimental Equipment

Because of the micro strain measurement data requirement, which requires high precision, the verification experiments are conducted on nuclear power valve. The information of the nuclear valve is shown in Table 1.

Table 1. The information of nuclear valve.

Valve type:	Push-off		
Spring rate:	10×23 N/mm		
Packing:	packing		
Modulus:	215.34		
Mode of action:	positive		
Diaphragm effective area:	1000 mm^2		
Valve diameter:	22 mm	Stem material:	SA479410
Valve stroke:	60 mm	Spring range:	80-240 kPa
Actuator type:	PZMA-7	Valve type:	HC-SF52000

Transmitter type: the range of 0-700 kPa, accuracy of 0.25 %;

Valve positioner: ABB V18347-204421000 type intelligent positioner;

Data acquisition equipment: NI9174, NI9219, NI9203, NI9265;

Auxiliary equipment: 4-20 ma signal generator, multimeter, regulated power supply;

Programming environment: Labview8.6.

The frequency of the pressure value and valve position is 1 k/s. Due to the fact that the largest sampling frequency of NI9219 is 100 points per second, friction is collected at 10 ms a point. However, for the measurement with mechanical device, this frequency is enough to meet the requirements of acquisition.

3.2. Friction Performance Experiment

1) Equipment calibration and platform structures.

There is a simple instruction of the experiment equipment calibration before the test. The calibration equipment in this experiment has three aspects: air pressure, the valve position and strain gauge.

Equipment calibration:

- Pressure testing is to check the output current, stroke, and each point linearity;
- The calibration of valve position detection is using another stetted valve positioner and dial indicator.
- Calibration of strain gauge is done by checking the resistances of the Wheatstone bridge balance, and the undertake software compensation in the program.

Platform structures:

- Before the test, first of all, a certain pressure is applied to make sure that the valve stem and the push rod are disconnected. Then, the strain rosette should be pasted at the top of the stem (note that the location of the strain rosette must be symmetric).
- With the strain rosette of Wheatstone bridge working properly, the valve positioner should be installed when the stem and the push rod are connected closely.
- After the valve positioner is installed, the output of the input signal of the transmitters and valve positioner are connected to the acquisition equipment. When the electrical connection is completed, the gas path needs to be done.

2) Experimental steps.

Friction test experiment consists of two experiments: measurement of valve spring pre-tightening force and steady-state friction test.

Experiment 1: The spring pre-tightening force measurement (can be test at the same time of platform structures):

- A certain pressure is applied to make sure that the valve stem and the push rod were disconnected. Then fix the feedback on the push rod, and install the valve positioner finished self-tuning
- Use a signal generator producing a 0.1 mA growth signal to the valve positioner until the point that stem begin to move, and the signal of stem displacement and diaphragm pressure should be gathered by data acquisition equipment.
- Set the start pressure P0 = 64.48 kPa when the stem begins to move, as shown in Fig. 2.
-

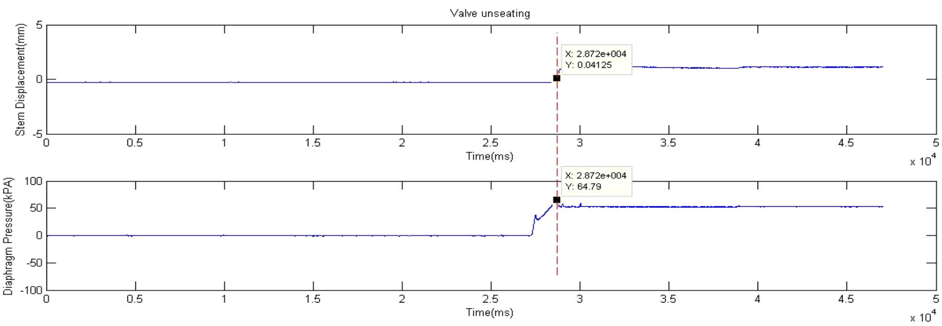


Fig. 2. The spring pre-tightening force.

Experiment 2: Steady-state friction test:

- Connecting the valve stem and the push rod and fixing the feedback on the push rod, then installing the valve positioner which is finished self-tuning;
- using a 4-20 mA signal generator to send 8 mA, 12 mA and 16 mA step signals, then using data acquisition equipment to gather the data at those steady state point respectively, as shown in Fig. 3.

Steady state ① is when the input signals is 8 mA, the state of balance between stem displacement, diaphragm pressure and packing friction (the data is an average of every steady state): Diaphragm Pressure P1 = 85.38 kPa; stem displacement PV1 = 14.46 mm; the friction f1 = 1348.5 N. The steady state ② and ③ can be obtained in the same way: P2 = 118.58 kPa, PV2 = 29.46 mm, f2 = 1417.6 N and P3 = 153.93 kPa, PV3 = 44.52 mm, f3 = 1321.2 N;

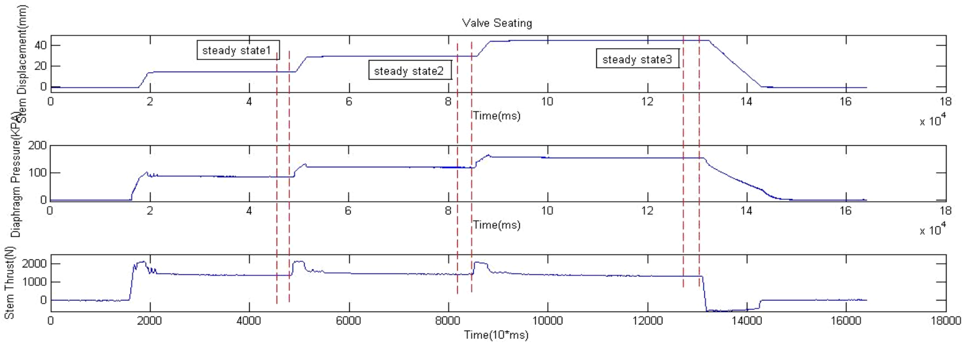


Fig. 3. Step signal test.

- Using the formula of stem displacement, diaphragm pressure and friction force:

$$f_{\text{theory}} = F_{\text{spring}} - F_{\text{diaphragm}} = \mathrm{k} \times \Delta \mathrm{x} \times \mathrm{n} - (\mathrm{P}_{\text{diaphragm}} - \mathrm{P}_0) \times S_{\text{effective area}},$$

where k is the Spring rate; Δx is the stem displacement; n is the number of spring; P_0 is the spring pre-tightening force.

The calculated theoretical values of friction compared with the measured ones are shown in Table 2.

Table 2. The theory of friction compared with the measured.

Term \ State	State 1	State 2	State 3
F_{theory}	1235.8N	1365.8N	1294.6N
F_{actual}	1348.5N	1417.6N	1321.2N

3.3. Problems and Improvements

1) External hardware module.

Through the formula to calculate:

$$F_p = P_{\text{diaphragm}} \times S_{\text{effective area}}$$

Accordingly, the accuracy of measurement of the transmitter directly affects the measurement of the stem force. In that the unit of pressure transmitter is kPa, small changes can bring large influence on measurement results. Taking the accuracy error of pressure transmitter as an example, when the accuracy error is 0.25 % (combining the range of our transmitter it means that the error is 1.75 kPa). This effect will become larger with the increase of the effective area of diaphragm. Therefore, the accuracy of pressure transmitter size is one of the dominant errors.

Secondly, the precision of the valve position transducer also has big impact. If the valve position cannot be obtained accurately, the F_k will have large error. It will lead to a larger error to the experimental data.

In addition, the strain gauge on the valve stem can also bring large errors to the experimental data, which may lead to the entire measurement to be invalid. The problem of strain gauge mainly contains two aspects:

- Strain gauge is not fully contact with the valve stem when paste the strain gauge.
- The welding of wiring place is not stable, which can lead to the error data when the stem is moving.

2) Data acquisition module.

From the introduction in the third chapter, the sampling frequency is 1000 Sample/s when collecting pressure and valve position signal. A sampling frequency of the strain signal to be 100 Sample/s can meet the requirements of mechanical strain collection in theory.

Considering the problems mentioned above, there are some solutions:

For this experiment, the precision of the sensor has a significant effect on the experimental results. Therefore, the improvement of the precision of the sensor can improve the accuracy of the experiment and make it more persuasive. In this experiment, the range of the pressure transmitter is 0~700 kPa, and its measurement accuracy is 0.25 %. Nowadays, products with measurement accuracy to be 0.05 % and 0.01 % can be brought which can greatly optimize the experiment results.

For the problem of strain gauge, there are two sets of solutions:

- choose better and more experienced technicians.
- use more advanced strain measurement sensor

The improvements to the acquisition module are achieved by changing some higher performance acquisition module, so that the consistency of the sampling frequency can be guaranteed.

4. The Fault Diagnosis of the Friction Parameter

4.1. The Introduction of Fault Equipment

This fault diagnosis [6-10] experiment is based on a single-seat gas open control valve which has the leakage failure. The leakage problem of valve can be separated into two parts: internal leakage and external leakage. This fault valve is an external one. Leakage is mainly due to packing leaking and stem broken. To verify the function of packing friction to a stem fault valve, three kinds of packing has been chosen at different packing gland pressures to ensure the reliability of the experiment. The information of the stem fault valve is shown in Table 3.

Table 3. The stem fault valve information.

Valve type:	Push-open		
Spring rate:	6*22.27 N/mm		
Packing:	Self-chosen		
Modulus:	198		
Mode of action:	reaction		
Diaphragm effective area:	280 mm^2		
Valve diameter:	10 mm	Stem material:	401 stainless steel
Valve stroke:	16 mm	Spring range:	20-100 kPa
Number:	1120	Work code:	400

Packing material: Graphite, tetrafluoroethylene and packing;

Transmitter model, acquisition equipment and testing equipment are the same as above;

4.2. Experiment and Result Analysis

1) Experiment 1: The spring pre-tightening force measurement.

Equipment calibration and platform construction in the validation experiments has been mentioned in the first experiment, and the pre-tightening force P0 = 19.96 kPa;

2) Experiment 2: fault detection test.

- selecting the material of the packing and assembling the strain gages the strain rosette should be pasted well; then installing the valve positioner which is finished self-tuning;
- setting the gland nut torque at 0N,6N and 12N;
- after the platform building is set correctly, make valve positioner to send 4-5 steps signal from initial to the full stroke, and back to the initial state (output step number is related to the gland pressure);
- Using LabVIEW program to obtain the data of stem displacement, diaphragm pressure and friction
- increasing the gland nut torque to 6N, and repeating steps (3) - (4);
- when the gland nut torque is 12N, change the packing materials to the next test;
- Put the data into Matlab to do some analysis (it will be discussed in the next section).

3) Data analysis

In the test, no matter what packing gland is been used, when the nut torque is 0N, the control valve is hard to control and the data is invalid. The valve stem force is as shown Fig.4:

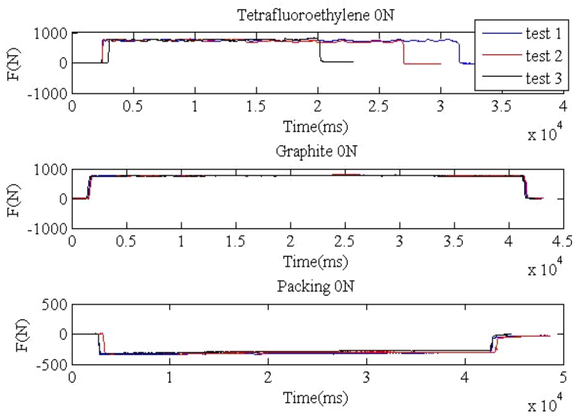


Fig. 4. Different packing in gland nut torque 0N.

Since the data in 0N torque is invalid, the analysis is based on the data in 6N and 12N torque, and specific steps are shown in Figs. 5-6.

- With the same packing, the stem displacement, diaphragm pressure and the friction test are shown below.

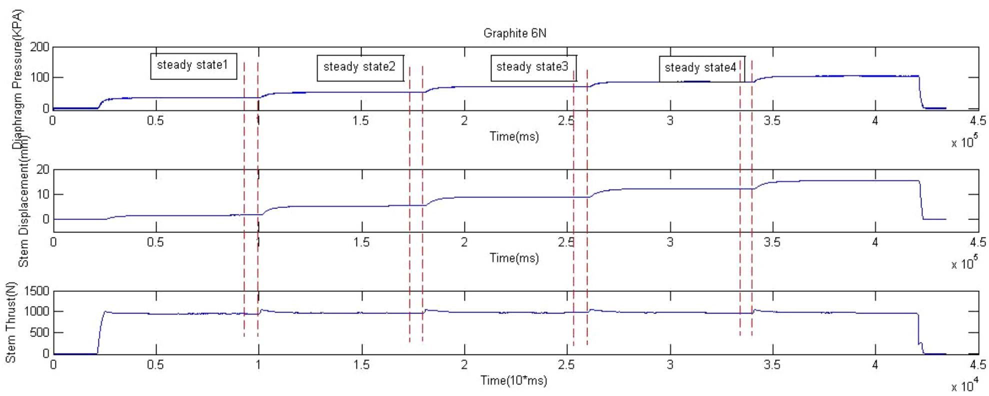


Fig. 5. Graphite in 6N torque.

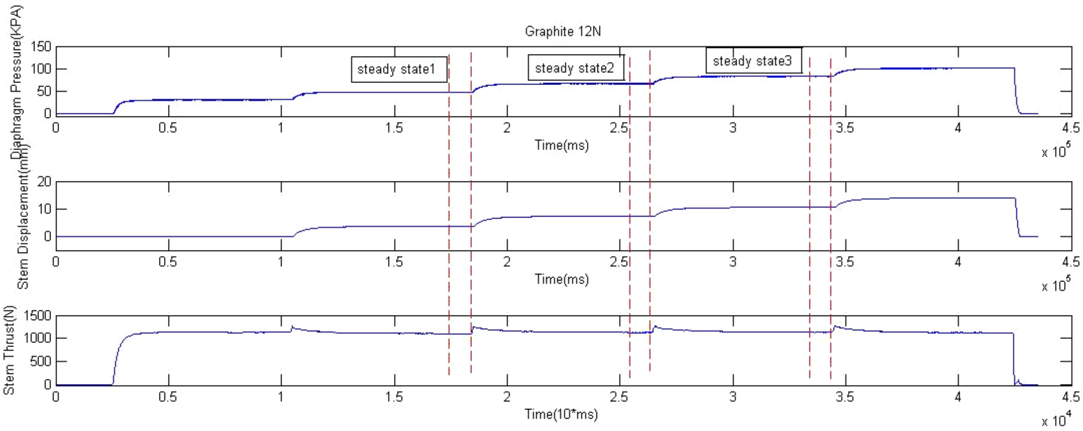


Fig. 6. Graphite in 12N torque.

From the pictures, the result shows that the higher the gland nut torque is, the larger packing frictions are, and four steady state data is shown as the following Table 4 and Table 5.

Table 4. The data of graphite in 6N torque.

Term / State	Diaphragm pressure (kPa)	Stem Displacement (mm)	F_{actual} (N)
Steady 1	34.89	1.55	958.3
Steady 2	51.53	5.08	969.5
Steady 3	69.60	8.71	986.2
Steady 4	86.29	12.03	986.5

Table 5. The data of graphite in 12N torque.

Term / Stage	Diaphragm pressure (kPa)	Stem Displacement (mm)	F_{actual} (N)
Steady 1	48.22	3.64	1146.7
Steady 2	66.83	7.34	1129.1
Steady 3	82.96	10.54	1133.4

With the above data, the comparative analysis between the theoretical value and the actual measured value can be obtained, shown as the Tables 6 and 7.

Table 6. Comparative analysis of graphite in 6N torque.

State / Term	State 1	State 2	State 3	State 4
F_{theory}	166.27N	110.46N	77.1N	50.7N
F_{actual}	958.33N	969.96N	986.20N	986.53N

Table 7. Comparative analysis of graphite in 12N torque.

State / Term	State 1	State 2	State 3
F_{theory}	220.12N	191.65N	166.82N
F_{actual}	1146.7N	1129.1N	1133.4N

The data of tetrafluoroethylene and packing in different gland nut torque can be acquired as Figs. 7-8:

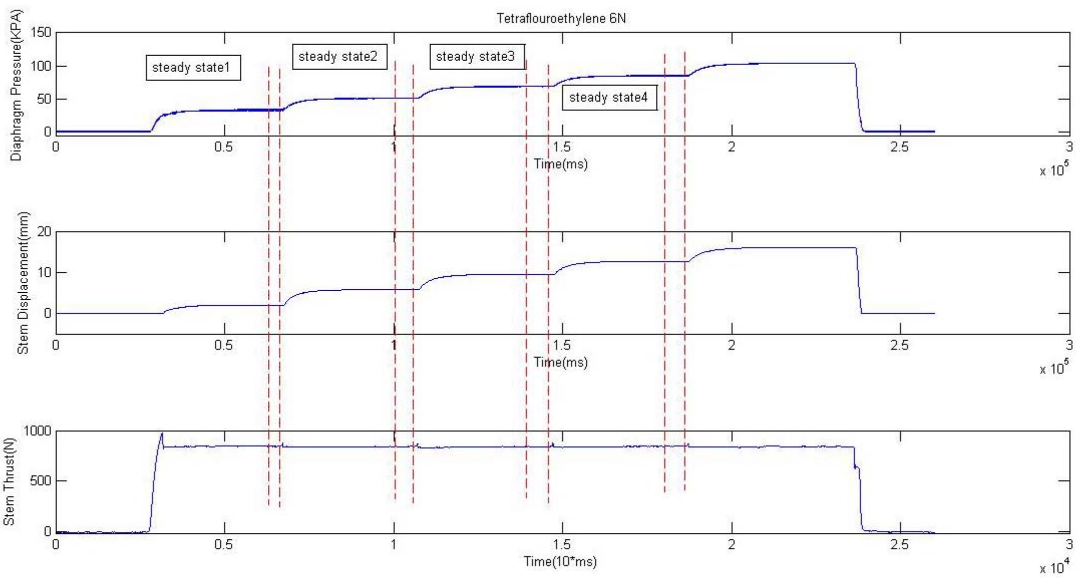


Fig. 7. Tetrafluoroethylene in 6N torque.

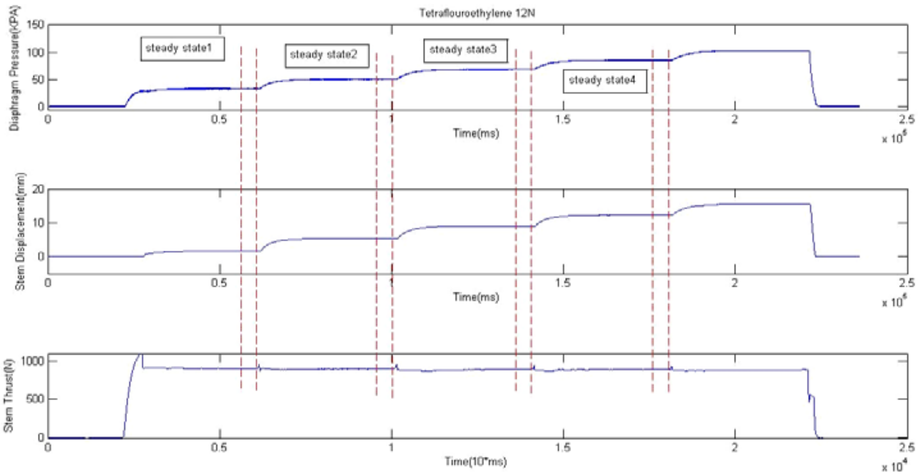


Fig. 8. Tetrafluoroethylene in 12N torque.

The comparative analyses between the theoretical value and the measured value are shown in Tables 8-11.

Table 8. The data of tetrafluoroethylene in 6N torque.

State \ Term	Diaphragm pressure (kPa)	Stem Displacement (mm)	F_{actual} (N)
Steady 1	33.49	2.02	846.33
Steady 2	51.19	5.78	842.68
Steady 3	69.13	9.46	841.06
Steady 4	85.47	12.66	847.17

Table 9. The data of tetrafluoroethylene in 12N torque.

State \ Term	Diaphragm pressure (kPa)	Stem Displacement (mm)	F_{actual} (N)
Steady 1	33.97	1.50	936.03
Steady 2	51.44	5.36	929.51
Steady 3	69.47	9.09	929.41
Steady 4	86.01	12.36	918.79

Table 10. Comparative analysis of tetrafluoroethylene in 6N torque.

Term \ State	State 1	State 2	State 3	State 4
F_{theory}	68.30N	8.10N	-34.69N	-54.44N
F_{actual}	846.33N	842.68N	841.06N	847.17N

Table 11. Comparative analysis of tetrafluoroethylene in 12N torque.

Term \ State	State 1	State 2	State 3	State 4
F_{theory}	150.14N	71.27N	23.68N	0.803N
F_{actual}	936.02N	929.51N	929.41N	918.79N

Form the comparison of the theoretical friction and the measured values in tetrafluoroethylene packing, there is a huge difference between the measured data and the theoretical ones, which will directly reflect the valve in a fault condition.

The graphite packing data comparison shows that both graphite and tetrafluoroethylene friction measurement have a great deviation, and it is not possibly due to the packing. Therefore, it is reasonable to say the reason of the problem is the stem failure. In order to improve the experimental accuracy, the experiment will be repeated in packing, and the data is shown in Figs. 9-10 and Tables 12-15.

Table 12. The data of packing in 6N torque.

State \ Term	Diaphragm pressure (kPa)	Stem Displacement (mm)	F_{actual} (N)
Steady 1	35.60	3.50	401.59
Steady 2	56.57	7.10	394.52
Steady 3	74.68	10.56	380.96
Steady 4	109.09	15.96	351.76

Table 13. The data of packing in 12N torque.

State \ Term	Diaphragm pressure (kPa)	Stem Displacement (mm)	F_{actual} (N)
Steady 1	35.87	2.48	440.71
Steady 2	53.12	6.01	439.52
Steady 3	70.62	9.52	431.37
Steady 4	86.36	12.51	420.07

Table 14. Comparative analysis of packing in 6N torque.

Term \ State	State 1	State 2	State 3	State 4
F_{theory}	23.95N	-33.16N	-42.84N	95.38N
F_{actual}	401.59N	394.52N	380.96N	351.76N

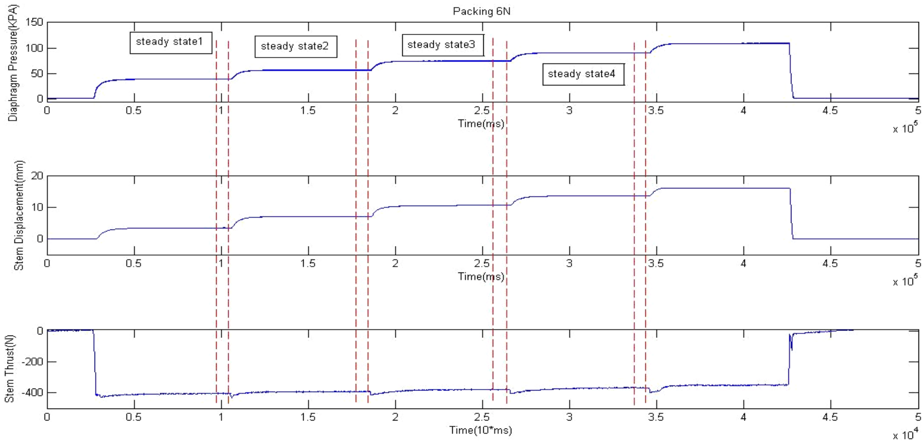


Fig. 9. Packing in 6N torque.

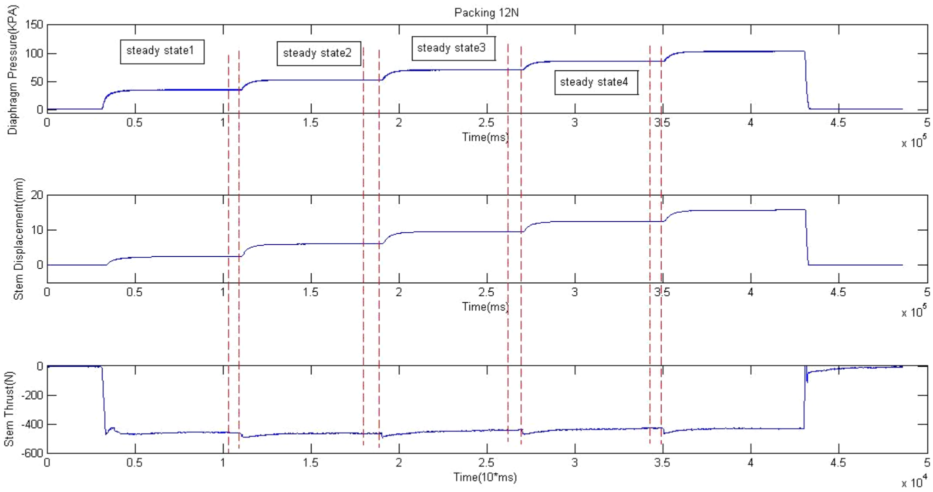


Fig. 10. packing in 12N torque.

Table 15. Comparative analysis of packing in 12N torque.

State / Term	State 1	State 2	State 3	State 4
F_{theory}	66.43N	25.46N	-5.37N	-11.44N
F_{actual}	440.71N	439.52N	431.37N	420.07N

Fig. 11 shows the stem problem:

Fig. 11. The breakage of the stem.

5. Conclusions

This paper offers a new valve static performance comprehensive index- packing friction index, and the theory is analyzed and validated in theory and experiment at the same time, this paper analyzes the problem involved in the experiment and gives reasonable solutions and suggestions. Finally, this friction parameter can be verified by diagnosing a fault valve to reflect the effect of the friction performance indicators.

Acknowledgements

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

References

[1]. Yanqing He, Control valve engineering design and application, *Chemical Industry Press*, Beijing, 2005.

[2]. Xidong Ming, The 1000 questions of regulator application, *Chemical Industry Press*, Beijing, 2006.

[3]. Massimo Sorli, Giorgio Figliolini, and Stefano Pastorelli, Dynamic model and experimental investigation of a pneumatic proportional pressure valve, *IEEE/ASME Transactions on Mechatronics*, Vol. 9, Issue 1, 2004, pp. 78-86.

[4]. Yasuhiro Sugimoto, Keisuke Naniwa and Koichi Osuka, Static and dynamic characteristics of McKibben pneumatic actuator for realization of stable robot motions, in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, San Francisco, CA, USA, 2011, pp-1817-1822.

[5]. EPRI Air-Operated Valve Evaluation Guide, EPRI TR-107322, *Electric Power Research Institute*, December 2006.

[6]. Yan Huang, Mi Zhou, Weixing Huang, Xiaozhong Li, Zhiyuan Luo, Valve Failure Analysis and Classification, *Valve*, Issue 6, 2006, pp. 41-44.

[7]. Yongfeng Zhao, The common fault diagnosis of pneumatic control valve, *Equipment Management and Maintenance*, 1, 2011, pp. 32-36.

[8]. Wu Song, Automatic control valve fault management and analysis, *Plastics Technology*, Issue 12, 2010, pp. 68-70.

[9]. Wang Xin, Yu Hongliang, Zhang Lin, Improved genetic algorithm and neural network method and the application in fault diagnosis of valve diesel engine, in *Proceedings of the IEEE Youth Conference on Information Computing and Telecommunications (YC-ICT)*, 28-30 November 2010, pp. 379-382.

[10]. Ahmed Hafaifa, Ahmed Zohair Djeddi, Attia Daoudi, Fault detection and isolation in industrial control valve based on artificial neural, *Control Engineering and Applied Informatic*, Issue 3, 2013, pp. 61-69.