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The Diagnosis of Internal Leakage of Control Valve Based on the Grey Correlation Analysis Method

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Abstract: The valve plays an important part in the industrial automation system. Whether it operates normally or not relates with the quality of the products directly while its faults are relatively common because of bad working conditions. And the internal leakage is one of the common faults. Consequently, this paper sets up the experimental platform to make the valve in different working condition and collect relevant data online. Then, diagnose the internal leakage of the valve by using the grey correlation analysis method. The results show that this method can not only diagnose the internal leakage of valve accurately, but also distinguish fault degree quantitatively. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Control valve, Fault diagnosis, Grey correlation analysis method, Flow characteristic, Internal leakage.

1. Introduction

With the continuous development of industrial automation, the control valve in the application of the control system is becoming more common. It has become an important part of the industrial automation system as terminal actuators of automatic regulating system [1].

Due to contact with the medium all the year, work in high temperature and high pressure, strong corrosion and other bad environment, it often appears different sorts of anomalies and faults. If these valve faults are not handed in time, it will affect the normal adjustment of the whole control system and ultimately affect the quality of the products and even endanger the production safety.

While some of the faults of valves are easy to be found so that we can take immediate steps to correct them once they appear. Some other faults are not easy to be detected before they cause huge losses, which has caused great difficulties for the maintenance and fault diagnosis of valves. The internal leakage is more common and belongs to this kind of fault.

Generally the ageing and broken inside sealing components of the valve and the separation of valve core or valve seat can all lead to internal leakage. And there is no accurate and effective diagnostic method for this problem [2].

According to the characteristics of internal leakage of valves, this paper establishes the diagnosis model by using grey correlation analysis method to diagnose internal leakage fault of valves. The results show that introducing the grey correlation analysis method in the fault diagnosis of valve, the calculation process can be simpler and more convenient, the amount of calculation can be smaller and the diagnosis results are reliable.

http://www.sensorsportal.com/HTML/DIGEST/P_2222.htm

2. Flow Characteristic

2.1. Discharge Coefficient

The discharge coefficient of valve is an indicator which measures the flow capacity of the valve. It refers to the volume flow or mass flow of the pipeline medium through the valve in unit time when the pipeline pressure is constant expressed in K_v. The greater the value of the discharge coefficient is, the greater the flow capacity of a valve and the smaller the pressure loss when the fluid flows through the valve. The discharge coefficient is related to the structure of valve, the pressure difference between two sides of the valve, the fluid density at the entrance and the characteristics of the fluid. It is dimensionless and the computational formula of it is as follows [3].

$$K_v = \frac{Q}{N}\sqrt{\frac{\rho_1}{\Delta p}} \tag{1}$$

where Q is the volume of the medium that goes through the valve in unit time measured by m^3/h; ρ_1 is the density of the medium in the pipeline measured by kg/m^3, Δp is the pressure difference between two sides of the valve measured by measured by KPa; N is the coefficient of engineering unit, N=0.1.

2.2. Flow Characteristic Curve

The meaning of flow characteristic of valve is when the valve pressure drop is constant, with the throttling element (disc) move from the closed position to its rated stroke, the relationship between discharge coefficient and the stroke of intercepting element (disc). Typically, these characteristics can be drawn on the graph which is the flow characteristic curve. The flow characteristic of valve is an important technical index and parameter which has very important significance in the application of valve.

According to the pressure drop between the two sides of control valves, the flow characteristics of control valve can be divided into inherent flow characteristic and work flow characteristic. The inherent flow characteristic is the flow characteristic which is got when the pressure drop between the two sides of control valves is constant, it's also known as the ideal flow characteristic. Control valve flow characteristic provided by the factory is the intrinsic flow characteristic [4].

Due to the actual working conditions, the pressure drop between two sides of valve can not be maintained. So the intrinsic flow characteristic will be distortion and become the work flow characteristic.

The intrinsic flow characteristic reflects the essential characteristic of regulating valve. While the work flow characteristic reflects the total characteristic which is made up of the characteristics of the valve and other components in the pipeline. So in order to reflect the advantages and disadvantages of control valve flow characteristics, the intrinsic flow characteristic should be the evaluation sample.

3. Grey Correlation Analysis Method

3.1. Grey Correlation Analysis Method

The grey correlation analysis method can quantitatively analyze the development and change of system dynamics. In essence, it is to compare the proximity between the evaluation object and the standard object. The closer they are, the bigger the correlation of the evaluation object. The relational sequence reflects the order of the proximity of the evaluation objects and the standard. If the standard object is an ideal object, the relational sequence will represents the order of the pros and cons of the evaluation objects. And the one whose correlation is the biggest is the best. This article based on the principle of grey correlation analysis method, compares the flow characteristics of control valve by using the correlation order to diagnose internal leakage fault of valve.

3.2. Modeling

1) Hypothesis, the number of fault standard feature vector of the system is m, which means the number of fault types to be diagnosed is m. And the number of the elements in each fault standard feature vector is n, which means the number of characteristic parameters for system to diagnose faults is n [5]. So we can set up a corresponding standard fault pattern characteristic matrix:

$$X_R = \begin{bmatrix} x_{r1} \\ x_{r2} \\ \vdots \\ x_{rm} \end{bmatrix} = \begin{bmatrix} x_{r1}(1) & x_{r1}(2) & \cdots & x_{r1}(n) \\ x_{r2}(1) & x_{r2}(2) & \cdots & x_{r2}(n) \\ \cdots & \cdots & \cdots & \cdots \\ x_{rm}(1) & x_{rm}(2) & \cdots & x_{rm}(n) \end{bmatrix} \tag{2}$$

The under test feature vector which comes from actual measurement signal is:

$$y_T = \left[y_t(1), y_t(2), y_t(3), \cdots, y_t(n)\right] \tag{3}$$

Then the next problem is how to determine the correlation degree between the under test feature vectors y_T and the standard feature vector matrix X_R.

2) The minimum absolute difference value of corresponding element of the under test feature

vectors y_T and the standard fault pattern feature vector in the standard feature vector matrix X_R is [6]:

$$\Delta_{\min} = \min_{1\le i\le m}\left[\min_{1\le i\le n}\left|y_t(j) - x_{ri}(j)\right|\right] \quad i = 1,2,\cdots,m;\ j = 1,2,\cdots,n \tag{4}$$

At the same time, we can get the corresponding maximum:

$$\Delta_{\max} = \max_{1\le i\le m}\left[\max_{1\le i\le n}\left|y_t(j) - x_{ri}(j)\right|\right] \quad i = 1,2,\cdots,m;\ j = 1,2,\cdots,n \tag{5}$$

3) $\zeta_{ij}(k)$ represents the correlation degree at k point between the under test feature vectors y_T and the standard feature vector matrix X_R [7].

$$\zeta_{ij}(k) = \frac{\Delta_{\min} + \rho\bullet\Delta_{\max}}{\left|y_t(j) - x_{ri}(j)\right| + \rho\bullet\Delta_{\max}} \quad i = 1,2,\cdots,m;\ j = 1,2,\cdots,n \tag{6}$$

where the ρ represents the distinguishing coefficient, which is a constant that can be determined in advance. And $0 \le \rho \le 1$, normally $\rho = 0.5$. The determine principles of ρ is [8]:

a) Fully embody the integrity of correlation degree

b) Robustness, when the abnormal value appears in the observation sequence of system factor. The concrete determination method is as follows:

$$\alpha_{\max} = \max_{1\le i\le m}\left[\max_{1\le i\le n}\left|y_t(j) - x_{ri}(j)\right|\right] \tag{7}$$

$$\alpha_v = \frac{1}{nm}\sum_{i=1}^{m}\sum_{j=1}^{n}\left|y_t(j) - x_{ri}(j)\right| \tag{8}$$

$$s_a = \frac{\alpha_v}{\alpha_{\max}} \tag{9}$$

The scope of ρ is $[s_a, 2s_a]$, and when $s_a \le \frac{1}{3}$, $s_a \le \rho \le 1.5s_a$; when $s_a \ge \frac{1}{3}, 1.5s_a < \rho \le 2s_a$.

4) Calculating correlation degree according to the correlation coefficient [9]:

$$r_i = \frac{1}{n}\sum_{k=1}^{n}\zeta_{ij}(k) \quad i = 1,2,\cdots,m;\ j = 1,2,\cdots,n \tag{10}$$

So that we can get the correlation degree sequence $R = [r_1, r_2, \cdots, r_m]$. When diagnose the faults of system with r_1, the advantage analysis thoughts should be used. That is to make correlation degree sequence from large to small in turn, we can get $r_s > r_h > r_p$. In the formula $s, h, p \in [1, m]$, which can reflect the order of correlation degree between the under test feature vector and the standard fault pattern feature vector of s, h, p. So it clears the order of the size of the possibility of seeing the performance model of under test signal as the standard fault pattern. In other words, when the correlation degree between the under test pattern sequence and a standard fault pattern sequences is biggest, we can think this under test pattern is belong to the corresponding standard failure pattern. Thus, we can realize the recognition of the fault modes [10].

4. Experimental Test

4.1. Experiment Platform

This experiment is carried out on the flow experimental bench, as shown in Fig. 1.

Fig. 1. Panoramic view of the experimental bench.

This experimental bench can imitate the industrial environment, high pressure difference, the simulation fault and dynamic flow experimental research under the temperature change environment. This experiment mainly uses a pneumatic control valve whose model number is ATS and flow characteristic is linear. The control valve is produced by Wuzhong Instrument Co., Ltd. Its adjustable ratio is 50 and the nominal diameter is 80. The stroke length of the stem is 30 mm. In addition, the positioner used in this experiment is produced by ABB whose model number is (TZID-C) V18345-1011221001. The principle diagram of the overall experimental bench as shown in Fig. 2.

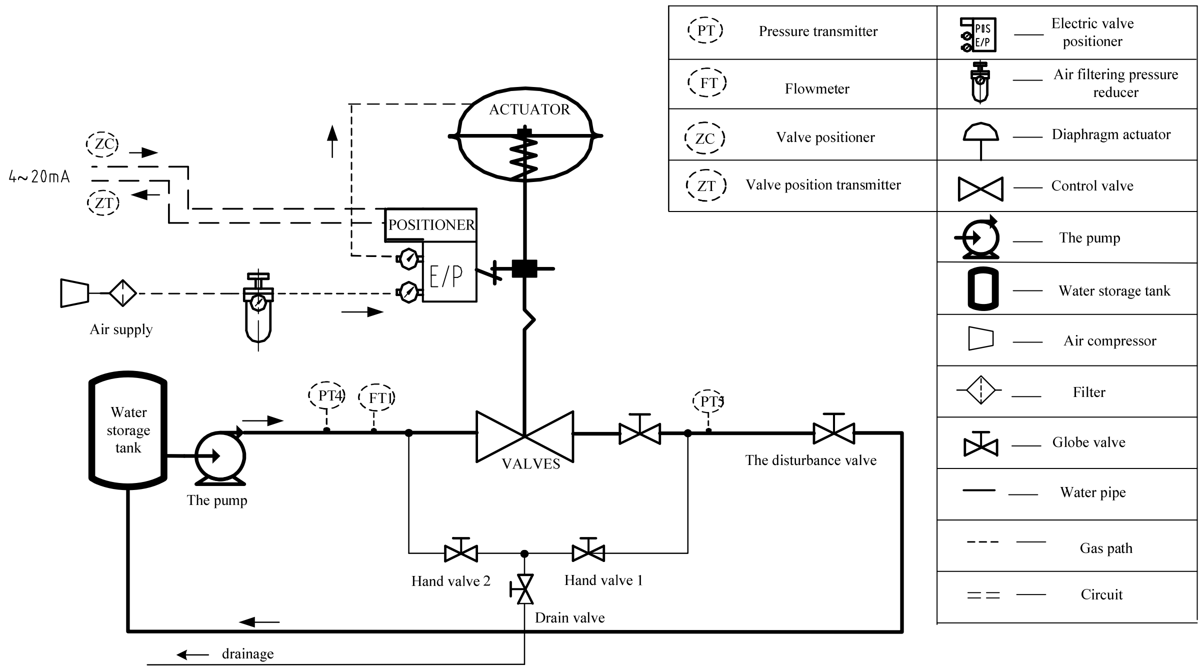

Fig. 2. The structure chart of flow experimental bench.

In the experiment, the chassis of data acquisition device is cDAQ-9174 which is manufactured by NI. And the sampling modules are NI9203, NI9265. The NI9265 output control signals to the positioner. The NI9203 is used to collect flow data and the pressure difference between the two sides of the valve. And PC software used to collect data is developed by ourselves base on the LabVIEW.

In the process of experiment, to run the flow experimental bench first so that the medium in pipeline is able to flow up (In this experiment the medium in pipeline is water). After it's running stable, change the opening of valve every time by the same amount finally realize its opening from 0 to 100 % through the the positioner. (In this experiment, the interval of the changing opening of valve every time is 12.5 %). At the same time, collect the flow data and the pressure difference between the two sides of the valve.

4.2. Experimental Scheme

First, when the valve works in normal situation, gradually increase the signal of valve positioner according to the order of 4 mA, 6 mA, 8 mA, 10 mA, 12 mA, 14 mA, 16 mA, 18 mA, 20 mA, so that the opening of the valve can be changed gradually. At the same time, collect the data of flow and pressure difference between the two sides of the valve under different opening. Then calculate the discharge coefficient and drawing the flow characteristic curve.

Then, fully open the hand valve 1 next to the main control valve, close the drain valve and gradually increase the opening of hand valve 2 (In this experiment, open the hand valve 2 from one times to three times). Make the valve work in internal leakage fault condition artificially. Use different opening of hand valve 2 to distinguish the severity of the internal leakage. Every time after increasing the degree of leakage, the flow characteristic should be tested. Finally, compare the flow characteristic curves which are got under different fault degree. And diagnose the fault of valve by using the grey correlation analysis method.

4.3. Experimental Scheme

4.3.1. Determination of Flow Coefficient

In this experiment, the opening of valve is from 0 to 100 % when test the flow characteristic curve and the interval of every opening is 12.5 %. So that the pressure difference between the two sides of the valve and the flow in the pipeline can be got under normal condition. The data as shown in Table 1.

According to formula (1), the discharge coefficient of the valve under normal condition can be got, as shown in Table 2.

Table 1. The data of flow and pressure difference when valve is under normal condition.

	Opening (%)								
	0	12.5	25	37.5	50	62.5	75	87.5	100
Pressure difference (KPa)	55.16	53.95	50.64	45.98	41.11	37.12	33.92	30.69	27.16
Flow (dm^3/min)	0.18	110.28	207.04	294.31	356.07	397.42	428.33	454.49	483.20

Table 2. The discharge coefficient when valve is under normal condition.

	Opening (%)								
	0	12.5	25	37.5	50	62.5	75	87.5	100
Discharge coefficient (Kv)	0.01	9.01	17.45	26.04	33.32	39.13	44.12	49.22	55.63

So that the contrast figure of actual flow characteristic curve tested under normal condition and the theoretical flow characteristic curve which is got from the data on the nameplate can be got, as shown in Fig. 3.

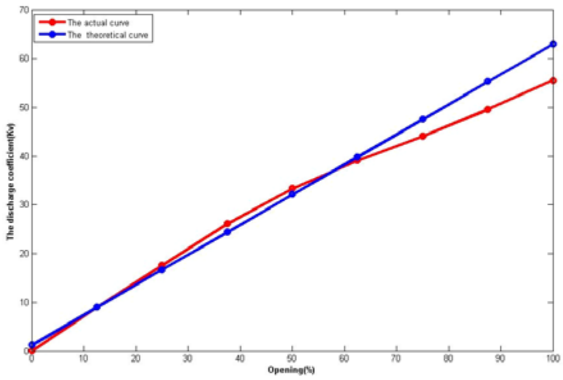

Fig. 3. The contrast figure of actual flow characteristic curve and theoretical flow characteristic curve.

Known from the contrast figure, there are lots of differences between the two kinds of flow characteristic curves. Because in the course of processing and manufacturing of valve, processing valves according to the design requirements, but due to the restriction of objective factors which include the accumulation of the tolerance of every part of the valve, the restrictions of processing technique and the uncertainty of human in the process of manufacturing. In the end the quality of the valve with large discreteness, so that there are lots of differences between the two kinds of flow characteristic curve.

Therefore, in order to be able to effectively diagnose the faults of the control valves which works in the actual conditions. The actual flow characteristic curve should be chosen as the evaluation standard.

4.3.2. Fault Diagnosis

In different level of internal leakage of the valve, the data of flow and the pressure difference can be got, as shown in Table 3.

According to formula (1), the discharge coefficient of the valve in different level of internal leakage can be got, as shown in Table 4.

Table 3. The data of flow and the pressure difference in different level of internal leakage.

		Opening (%)								
		0	12.5	25	37.5	50	62.5	75	87.5	100
One laps	**Flow(dm^3/min)**	46.7145	143.7946	241.3591	319.3334	378.8265	415.7568	443.5568	472.3344	495.1052
	Pressure difference(KPa)	54.8484	52.7767	48.7859	43.5806	38.3879	34.7117	31.4065	27.7038	25.1551
Two laps	**Flow(dm^3/min)**	49.9886	146.9435	245.7141	325.9856	384.3916	418.2869	445.2663	476.6514	495.0757
	Pressure difference(KPa)	54.8142	52.6116	48.6780	43.4798	38.2241	34.3890	31.2137	27.6897	25.0736
Three laps	**Flow(dm^3/min)**	50.5845	149.4400	245.4779	327.6229	383.1799	419.8609	446.2580	478.0707	495.0753
	Pressure difference(KPa)	54.8505	52.6230	48.6593	43.5683	38.1713	34.3554	31.2306	27.6503	24.8371

Table 4. Discharge coefficient.

		Opening (%)								
		0	12.5	25	37.5	50	62.5	75	87.5	100
Discharge coefficient (Kv)	**One laps**	3.79	11.88	20.73	29.02	36.69	42.34	47.49	53.84	59.23
	Two laps	4.05	12.16	21.13	29.66	37.30	42.80	47.82	54.35	59.32
	Three laps	4.10	12.36	21.11	29.78	37.21	42.98	47.91	54.55	59.60

From the Table 4, the flow characteristic curve that is tested under the normal condition and the different degree of internal leakage can be got, and the contrast figure as shown in Fig. 4.

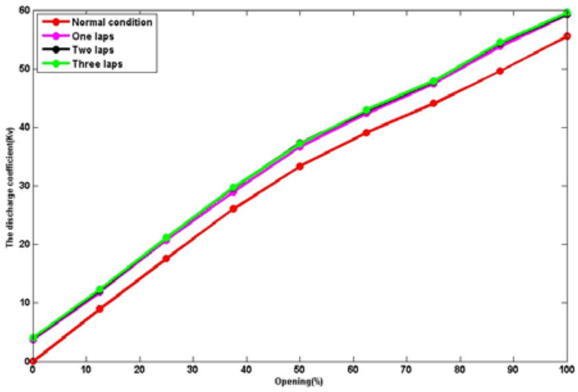

Fig. 4. The contrast figure.

Known from the contrast figure, once the hand valve is open, the valve works in fault condition immediately. But as the degree of the fault is deepening, the change of the distortion degree of flow characteristic is not obvious. So there is no way to distinguish the three different fault degrees through the qualitative diagnosis.

5. Data Analysis

First, according to the discharge coefficient of different opening in the normal condition. The standard vector X_1 can be got,

$$X_1 = \begin{bmatrix} 0.02 & 8.98 & 17.59 & 26.12 & 33.36 & 39.09 & 44.10 & 49.63 & 55.53 \end{bmatrix}$$

Then, according to the discharge coefficient of different opening when the valve is in the internal fault. The under test feature vector y_1 can be got,

$$y_1 = \begin{bmatrix} 3.79 & 11.88 & 20.73 & 29.02 & 36.69 & 42.34 & 47.49 & 53.84 & 59.23 \\ 4.05 & 12.16 & 21.13 & 29.66 & 37.30 & 42.80 & 47.82 & 54.35 & 59.32 \\ 4.10 & 12.36 & 21.11 & 29.78 & 37.21 & 42.98 & 47.91 & 54.55 & 59.60 \end{bmatrix}$$

In order to clear the diagnosis effect of the method for the internal leakage faults of valve. The standard vector can be also a set of data to be detected. So the feature vectors y_2 used to diagnose fault can be got,

$$y_2 = \begin{bmatrix} 0.02 & 8.98 & 17.59 & 26.12 & 33.36 & 39.09 & 44.1 & 49.63 & 55.53 \\ 3.79 & 11.88 & 20.73 & 29.02 & 36.69 & 42.34 & 47.49 & 53.84 & 59.23 \\ 4.05 & 12.16 & 21.13 & 29.66 & 37.30 & 42.80 & 47.82 & 54.35 & 59.32 \\ 4.10 & 12.36 & 21.11 & 29.78 & 37.21 & 42.98 & 47.91 & 54.55 & 59.60 \end{bmatrix}$$

According to the formula (3), (4), (5), the correlation coefficients ζ of valve in each work condition can be got,

$$\zeta = \begin{bmatrix} 1.0000 & 1.0000 & 1.0000 & 1.0000 & 1.0000 & 1.0000 & 1.0000 & 1.0000 & 1.0000 \\ 0.3434 & 0.4048 & 0.3852 & 0.4042 & 0.3719 & 0.3773 & 0.3675 & 0.3184 & 0.3473 \\ 0.3281 & 0.3828 & 0.3574 & 0.3573 & 0.3329 & 0.3469 & 0.3461 & 0.2942 & 0.3417 \\ 0.3255 & 0.3681 & 0.3584 & 0.3497 & 0.3382 & 0.3360 & 0.3405 & 0.2857 & 0.3258 \end{bmatrix}$$

Finally, according to the formula (9), the correlation degree sequence R can be got,

$$R = \begin{bmatrix} 1, 0.3689, 0.3431, 0.3364 \end{bmatrix}$$

That means, $r_0 = 1$, $r_1 = 0.3689$, $r_2 = 0.3431$, $r_3 = 0.3364$ .Sorting them according to the size, the result is $r_0 > r_1 > r_2 > r_3$. The diagnosis result according to the grey correlation analysis method can be got. The r_0 is better than r_1, the r_1 is better than r_2, and the r_2 is better than r_3. It is consistent with the actual situation.

6. Conclusions

This paper uses the experimental data to show the effectiveness of diagnosing the internal leakage fault of valve by using the grey correlation analysis method. For this method, the calculation amount is small, easy to master and the diagnosis result is consistent with the results of qualitative analysis. What's more, the method can quantitatively distinguish the fault degree, which is a very potential diagnosis method of the faults of valves.

References

[1]. Guang Yang, Xiaoping Wu, Research on fault diagnosis for the ship hydraulic equipment based on fuzzy grey relational model, *Journal of Wuhan University of Technology*, Vol. 31, Issue 5, 2007, pp. 788-791.

[2]. M. A. A. S. Choudhury, S. L. Shah, N. F. Thornhill, Diagnosis of process nonlinearities and valve stiction data driven approaches, *Springer*, 2007.

[3]. He Yan Qing, Qiu Xuan Zhen, Yang Jie, Wang Wei Guo, Control valve engineering design and application, *Chemical Industry Press*, Beijing, 2005.

[4]. Wang Genping, Regulating valve the flow characteristic of correction, *Metrology & Measurement Technique*, Vol. 4, 2004, pp. 21-23.

[5]. Zheng Xuanrong, Grey correlation analysis on the sensitive factors of plastic zone extension of surrounding rock, *Applied Mechanics and Materials*, Vol. 348-349, 2013, pp. 1210-1216.

[6]. Shunxiang Wu, Yongjie Huang, Lihua, Lin, A grey correlation analysis method based on the interval deviation degree, in *Proceedings of the 6th International Conference on Fuzzy Systems and Knowledge Discovery*, Vol. 7, 2009, pp. 8-12.

[8]. Yong Chun Cheng, Peng Zhang, Yu Bo Jiao, Jing Lin Tao, Ye Dan Wang, Grey correlation analysis method to analyze the influence factors of attenuated performance of asphalt mixture under water-temperature-radiation cycle action, *Applied Mechanics and Materials*, Vol. 361-363, 2013, pp. 1857-1860.

[9]. Geng Wenshuang, Grey correlation analysis of influence factors on daily water-injection rate of each well group, *Advanced Material Research*, Vol. 641-642, 2013, pp. 105-108.

[10]. S. W. Zhang, T. X. Lan,, X. F. Fang, Application of grey correlation analysis on tool selection, *Advanced Materials Research*, Vol. 97-101, 2010, pp. 2485-2488.
