Research on error compensation method of multi-channel ultrasonic flowmeter based on SVM

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Abstract

The measurement process of multi-channel ultrasonic flowmeter is affected by the distribution of flow field in the pipeline, which makes the measurement results of sound channel have large errors, and finally leads to large errors in the integration results of flow. Especially when the ultrasonic flowmeter is installed near the rear of the valve, elbow and other spoiler, the influence of the flow field distribution in the pipeline on the measurement results of the ultrasonic flowmeter is difficult to avoid. Aiming at the distribution of the flow field in the pipeline behind the gate valve and its influence on the multi-channel ultrasonic flowmeter, this paper studies the influence of the opening of the gate valve, the distance between the ultrasonic flowmeter and the gate valve and the installation angle of the gate valve on the measurement error of the multi-channel ultrasonic flowmeter through CFD simulation experiments, and puts forward the error compensation model of the multi-channel ultrasonic flowmeter based on SVM, The measurement results of multi-channel ultrasonic flowmeter caused by the flow field distribution behind the gate valve are compensated, and the compensation results are compared with the flow integration results. It is found that the compensation model based on SVM proposed in this paper has better compensation effect.

1. Introduction

The measurement accuracy of flowmeter is an important index to measure whether the flowmeter meets the measurement requirements, and is an important basis for improving the structure and parameters of flowmeter or error compensation. With the continuous progress of technology, flowmeter has been applied to industrial production, agricultural irrigation, chemical products manufacturing, aerospace development, national defense and medical construction and other fields. In the field of oil exploitation, flowmeter is used in all aspects of the industrial chain, such as oil exploitation, oil transportation and oil trade. Flowmeter is needed for accurate measurement [1]. In the chemical industry, instruments need to be used to effectively inspect the production process to ensure the quality of chemical products [2]. In the field of power production, flowmeter plays an important role in the measurement of the flow of gas, liquid, steam and other media. Its accuracy directly affects the economic benefits [3]. In other industries, the accurate measurement of flowmeter also plays an important role. However, restricted by its own sensitive elements and measuring circuits[4], the measurement results of the flowmeter are easily affected by the measurement environment, such as temperature, humidity, air pressure, density, vibration signals, etc[5]. Therefore, in-depth research on the error compensation method of the flowmeter is very important to improve the measurement accuracy of the flowmeter[6].

In this paper, the measurement error and influencing factors of plug-in ultrasonic flowmeter are studied[7]. Through CFD simulation experiments, an error compensation model based on support vector machine is established. The support vector machine compensation model predicts the measurement error[8] according to the specific measurement working conditions parameters, such as gate valve opening, gate valve distance, etc., and compensates the measurement results of the flowmeter through the error compensation model, so as to improve the measurement accuracy of the ultrasonic flowmeter. With the adjustment of kernel function parameters[9], the error compensation effect of the compensation model for the ultrasonic flowmeter working behind the gate valve in the straight pipe section will be better and better, and the accuracy will also be improved.

2. Principle of ultrasonic flowmeter

2.1 Basic principle of ultrasonic flowmeter

According to the different measurement principles of ultrasonic flowmeter, it can be divided into wave velocity migration method, Doppler method, noise method and propagation velocity method. Since this paper focuses on the error compensation method of time difference ultrasonic flowmeter, this paper focuses on the working principle of time difference ultrasonic flowmeter.

The time difference ultrasonic flowmeter can be divided into mono channel and multi-channel by the number of channels. The mono channel ultrasonic flowmeter pays more attention to the design of topology, mainly Z-type, V-type, W-type, n-type, etc., and the commonly used ones are Z-type and V-type[10]. This paper studies that the plug-in ultrasonic transducer is composed of multiple Z-type installed transducer pairs. Since the working principle of solving the line average velocity is similar, Z-type is introduced here as an example[11]. As shown in Figure 1.

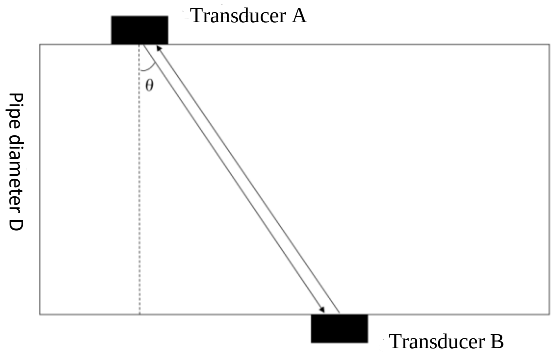

Figure 1: Type Z

transducer a. The relationship between wave velocity, water velocity and time is shown in formulas (1) and (2):

$$c + v = \frac{D/cos\theta}{t_1} \tag{1}$$

$$c - v = \frac{D/cos\theta}{t_2} \tag{2}$$

From formula (1) and formula (2):

$$c = \frac{D/cos\theta}{2}\left(\frac{1}{t_1} + \frac{1}{t_2}\right) \tag{3}$$

$$v = \frac{D/cos\theta}{2}\left(\frac{1}{t_1} - \frac{1}{t_2}\right) \tag{4}$$

Because the speed of water in the axial direction of the pipe $V = v/sin\theta$, So the velocity of water V is

$$V = \frac{D/cos\theta}{2sin\theta}\left(\frac{1}{t_1} - \frac{1}{t_2}\right) \tag{5}$$

Flow Q is the flow velocity V of water multiplied by the cross-sectional area S of water, then Q is

$$Q = V \cdot S = \frac{D/cos\theta}{2/sin\theta}\left(\frac{1}{t_1} - \frac{1}{t_2}\right) \cdot \frac{\pi D^2}{4} = \frac{\pi D^3}{8sin\theta cos\theta}\left(\frac{1}{t_1} - \frac{1}{t_2}\right) \tag{6}$$

Since the flow is affected by many factors under actual working conditions[12], the calculated flow needs to be corrected, that is, multiplied by the correction coefficient K, so the flow Q is

$$Q = \frac{k\pi D^3}{8sin\theta cos\theta}\left(\frac{1}{t_1} - \frac{1}{t_2}\right) \tag{7}$$

Where:

k -- correction coefficient

θ—— Ultrasonic incidence angle

D - pipe diameter

2.2 Error source of ultrasonic flowmeter

Due to the limitations of on-site installation conditions, ultrasonic flowmeter is often installed behind the gate valve[13]. The measurement accuracy of the ultrasonic flowmeter installed behind the gate valve is not only affected by the installation error of the transducer, temperature and flow fluctuation, but also by the unstable flow field caused by the valve. The temperature and fluctuation in the actual pipeline have little influence, while the flow field is greatly affected by the flow field factors such as the opening of the gate valve, the rotation angle of the gate valve, the distance between the flowmeter and the gate valve, and the pressure of the pipe wall, It brings great error to the measurement of ultrasonic flowmeter. In order to describe the change of flow field more specifically, the asymmetry coefficient, which is the flow field evaluation index suitable for the gate valve in the straight pipe section, is also introduced. In the following work, the influence of flow field changes on the measurement accuracy of ultrasonic flowmeter was studied in depth.

3. Principle of support vector machine

3.1 Support vector machine regression principle

The basic idea of SVM regression is to map data X to high-dimensional feature space through a nonlinear mapping, and carry out linear regression in this space[14]. The general regression problem can be expressed as, Given l training samples, the learning machine learns the relationship between input and output variables. Suppose the training data $\{(x_i, y_i), i = 1,2 \ldots, l\}$, where $x_i$belongs to R_n, is the n-dimensional input value of the ith learning sample point, y_i belongs to R, is the corresponding target value, and l is the number of training samples. The goal is to find a function $f\ (x)$ that can better approximate the stored sample points. In general, the estimation function of SVM is expressed as follows

$$f(x) = \langle \omega^t \cdot < (x) \rangle + b \tag{8}$$

Where $f\ (x)$ is a regression function, ω And B are the normal vector and offset of the regression function respectively. Then the standard support vector regression algorithm can be described as the following problem, that is

$$min \frac{1}{2} w^2 + C \sum_{i=1}^{l} (\xi_i + \xi_i^3) \tag{9}$$

$$s.t \begin{cases} y_i - \langle \omega^t \cdot < (x_i) \rangle - b \leq \varepsilon + \xi_i \\ \langle \omega^t \cdot < (x) \rangle + b - y \leq \varepsilon + \xi_i^3 \\ \xi_i, \xi_i^3 \geq 0, i = 1,2, \ \ ,l \end{cases} \tag{10}$$

Where C is the penalty factor; $\xi_i$is the relaxation variable; ε Is a loss function.

It is solved by Lagrange multiplier method, and Lagrange multiplier is introduced α_i, α_i^3. At the same time, the kernel function $K(x_i, \ x_j) = \langle < (x_i) \cdot < (x_j) \rangle$ is introduced to solve the Lagrange function. After derivation, its dual optimization problem can be obtained. After solving the above quadratic optimization problem, the general formula can be rewritten as

$$f(x) = \sum_{i=1}^{i} (\alpha_i -, \alpha_i^3)\langle < (x_i) \cdot < (x_j)\rangle + b$$

$$= \sum_{i=1}^{i} (\alpha_i -, \alpha_i^3) K(x_i, \ x_j) + b \qquad (11)$$

Where b is calculated by support vector; Kernel function K is any symmetric kernel function satisfying Mercer condition, which corresponds to the dot product of feature space. Commonly used kernel functions include linear kernel function, polynomial kernel function and radial basis kernel function.

There is a one-to-one correspondence among kernel function, mapping function and feature space. After the kernel function $K(x_i, \ x_j)$ is determined, it means that the mapping function and feature space have been determined. If the kernel parameters change, the mapping function will also change accordingly, and the subspace distribution of sample data will also change accordingly. At the same time, each data subspace uniquely corresponds to the optimal classification hyperplane. The complexity of the optimal classification surface depends on the dimension of the data subspace. Therefore, choosing the appropriate kernel function parameters can establish a suitable support vector machine model, which plays a key role in the final error compensation.

Penalty factor C has a certain control effect on the complexity of the model. Based on a specific range, penalty factor C is significantly positively related to the fitting degree of the sample data, but too large C will lead to over fitting.

3.2 Principle of SVM compensation model

Through the analysis of the principle and error source of ultrasonic flowmeter[15], the flow field has the greatest impact on the ultrasonic flowmeter. Therefore, when designing the support vector machine model, the training model is built based on the factors that affect the fluid flow field after the gate valve in the straight pipe section. Take the gate valve opening, gate valve distance, gate valve rotation angle and asymmetry coefficient as the model input, and the difference (i.e. error) of the surface average flow rate 45d behind the gate valve in the plug-in ultrasonic flowmeter as the output value of the model. After the model is trained, the output value of the model is accumulated with the measured value of the ultrasonic flowmeter, so as to achieve the function of flow compensation. Based on this, the support vector machine model is built, and the compensation model in model training is shown in Figure 2

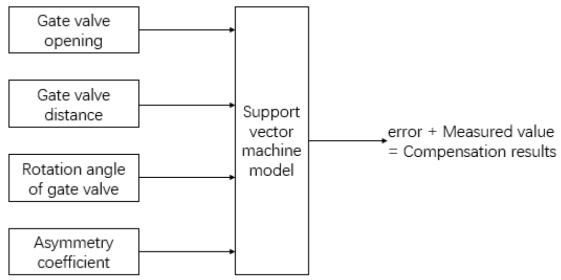

Figure 2: Support vector machine compensation model diagram

The asymmetry coefficient is a quantitative index to describe the internal distribution of the flow field. According to the average velocity of each channel line of the sample of the multi-channel ultrasonic flowmeter, the asymmetry coefficient of the flow field is defined as:

$$\alpha = \frac{(v_1+v_5) - (v_4+v_8) + (v_2+v_6) - (v_3+v_7)}{2} \qquad (12)$$

Where, v_1、v_2、…、v_8 is the line average velocity of channels 1, 2, …, and 8, respectively.

The compensation algorithm flow is shown in Figure 3.

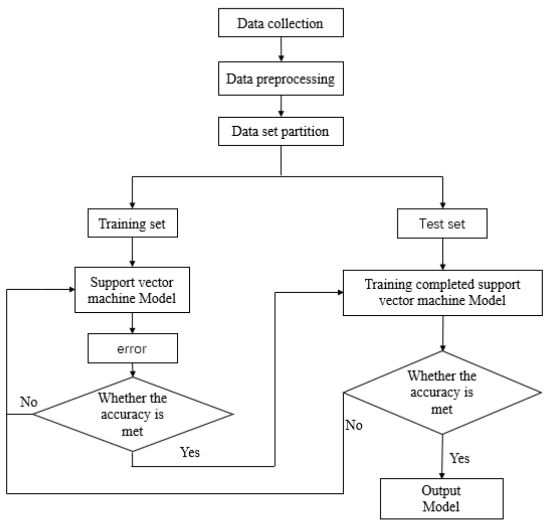

Figure 3: Flow chart of support vector machine algorithm

4. Simulation experiment research

In order to verify the compensation effect of SVM algorithm, CFD simulation is used to import the pipeline model for simulation calculation, and the velocity data of eight channels are extracted. The simulation process is as follows. Figure 4 is the design drawing of simulation.

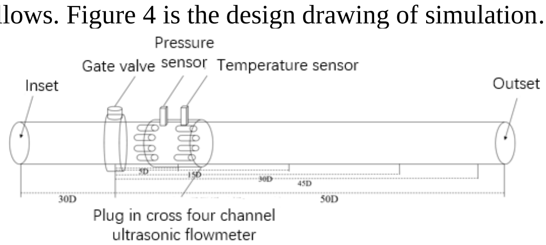

Figure 4; Simulation pipeline design drawing

CFD simulation calculation process:

(1) The long straight pipeline is equipped with a gate valve with adjustable opening. The position of the gate valve is shown in Figure 5. The opening of the gate valve is set to 50% and 60%, and the surface average velocity 45D away from the gate valve is taken as the standard velocity.

(2) The rotation angle of the gate valve is set to 0°, 10°, 20°, 30°, 40°, 50 °, 60 °, 70°, 80°, 90 °.

(3) Set cross sections at 3D, 5D, 10D, 15D and 20D behind the gate valve to derive the flow rate at each position for analysis.

(4) Extract the axial velocity of each channel, use the circular integral method, carry out weighted processing, and analyze the error.

The parameter settings are shown in Table 1:

Table 1: Simulation experiment parameter settings:

Gate valve opening	50% 60%
Inlet velocity	3m/s
Gate valve distance	3D、5D、10D、15D、20D
Rotation angle of gate valve	0°、10°、20°、30°、40°、50°、60°、70°、80°、90°

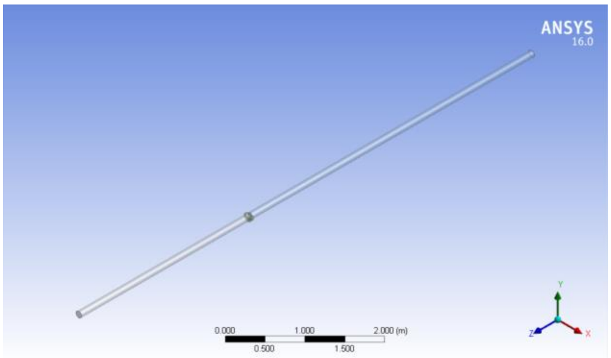

Figure 5 Gate valve model with 50% opening and 0° rotation angle

During the simulation calculation, when the hydraulic diameter is set to 0.1M and the flow velocity at the inlet of the pipe is set to 3m/s, the calculation is carried out after initialization. The flow velocity at the position 45d away from the gate valve is considered to be a steady developing flow field. Take its surface average flow velocity as the agreed value, and compare it with the integral velocity to solve the relative error. After the calculation is completed, the opening of the gate valve is set to 50%. Repeat the calculation, and extract the simulation velocity values of eight sound channels at different distances, Calculate the error and symmetry, as shown in the figure, the gate valve opening is 50%, and the rotation angle is 0 °. Table 2 shows the simulation data extracted and calculated at different positions.

Table 2: Simulation data at different locations:

Channels	**Distance from gate valve position**		
	2D	3D	5D
line_1	0.0842	1.3960	1.7960
line_2	0.0591	1.3970	1.7945
line_3	2.7720	2.8380	2.8650
line_4	2.7420	2.8445	2.8720
line_5	3.7120	3.4270	3.3120
line_6	3.7280	3.4320	3.3100
line_7	3.0190	2.4800	2.3860
line_8	2.9880	2.4630	2.3880
v-integral	2.8950	2.9510	2.9610
v	2.9650	2.9650	2.9650
error/%	2.360877	0.472175	0.134907
Symmetry	4.038125	1.6635	1.0345

5. Error compensation and result analysis of ultrasonic flowmeter based on SVM

5.1 Support vector machine model training

a. Take the gate valve opening, symmetry, the distance between the transducer and the gate valve, and the rotation angle of the gate valve as the input dimensions to extract the corresponding flow rate.

b. Take the surface average velocity at 45d as the agreed value, and calculate the error between each velocity extracted by a and the agreed value as the output dimension.

c. Randomly disturb the data set, divide the training set and test set according to the proportion of 7:3, input the training set into the support vector machine model for training, adjust the model parameters through the test set results, so that the fitting effect is the best, and the model training is completed. Table 3 and table 4 are test set and training set respectively.

Table 3: Training set

Gate valve opening	**Rotation angle of gate valve**	**Gate valve distance**	**Symmetry**	**Error**
50	10	15	0.2870	0.2
50	70	17.5	0.0445	0.3
50	50	10	0.6990	3.3
50	80	15	0.3265	0.6
50	40	17.5	0.3570	0.3
50	30	10	0.0630	2.6
50	40	15	0.4645	0.9

60	40	17.5	0.0510	0.1
…	…	…	…	…
60	30	5	0.8955	1.3

Table 3: Test set

Gate valve opening	Rotation angle of gate valve	Gate valve distance	Symmetry	Error
50	10	20	0.0175	0.1
50	0	3	7.4170	1.4
50	60	10	0.1315	3.4
60	50	17.5	0.2695	2.5
…	…	…	…	…
60	0	5	0.2005	0.5

Because the error is too small and the fitting effect is too poor, here we multiply the error by 100 to train and adjust the parameters.

d. The predicted error is compensated to the measured value at a, the compensated result is obtained, and the error is analyzed.

5.2 Results and analysis

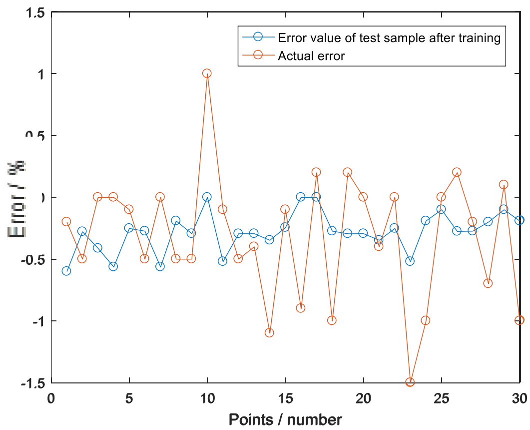

Figure 6 Convolution error and integration error comparison chart

It can be seen from figure 6 that the relative error range after support vector machine compensation is smaller than the integration error. The maximum relative error of integration is 1.012%, the maximum relative error of support vector machine is 0.5142%, the variance of integration is 0.3523, and the variance of support vector machine is 0.1816. Compared with the results after integration, the relative error and variance of the results after error compensation by support vector machine are smaller, so in theory, the method of support vector machine can compensate the measurement results of cross four channel ultrasonic flowmeter, and the error of the compensated results is smaller and more stable.

6. Conclusion

Aiming at the error produced in the measurement of ultrasonic flowmeter, this paper proposes a new error compensation method based on vector machine, establishes training samples and test samples through experimental data, uses support vector machine to fit and approximate the flow error model of ultrasonic flowmeter, and then compensates according to the prediction error. The simulation results show that the method provided in this paper can effectively compensate the errors in the experiment and improve the measurement accuracy of ultrasonic flowmeter. SVM algorithm has the characteristics of simple programming and fast algorithm calculation, especially suitable for small sample learning.

7. Acknowledgement

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References

[1] Zhang Qiang, song bin, Liu Dingfa Analysis of technical difficulties in field use of moisture flowmeter [J] Petroleum and natural gas chemical industry, 2018, 47 (4): 7

[2] Weng Tao Analysis on the development and application of chemical automation instruments [J] Science and technology innovation, 2014 (8): 85-85

[3] Pang Bing, Yin Ming Application of electromagnetic flowmeter in industrial water measurement of steel plant [J] Shandong industrial technology, 2015 (18): 1

[4] Wang Mingjun, Zhang Zhonghua, Zhong Ruiping Application of electromagnetic flowmeter in industrial water measurement of steel plant [J] Henan science and technology, 2013, Issue 9

[5] Iooss B, Lhuillier C, Jeanneau H. Numerical simulation of transit-time ultrasonic flowmeters: uncertainties due to flow profile and fluid turbulence[J]. Ultrasonics, 2002, 45 (9): 1009-1015

[6] Qin fan Design and implementation of high precision ultrasonic flowmeter [D] Xijing university, 2019

[7] Ning Chen, Gu Yu, Zhou Kangyuan, Chen ting Design of a new high-precision ultrasonic flowmeter [J] Acoustic technology, 2013, 22 (4): 259-261

[8] Wang xianni Research status of ultrasonic flowmeter [J] Industrial measurement, 2015, Volume 25 (6): 38-39, 50

[9] Bjurström J, Wingqvist G, Yantchev V, et al. Temperature compensation of liquid FBAR sensors[J]. Journal of Micromechanics and Microengineering, 2007, 17(3): 651

[10] Gubinyi Z, Batur C, Sayir A, et al. Electrical properties of PZT piezoelectric ceramic at high temperatures[J]. Journal of Electroceramics, 2008, 20(2):95-105

[11] Shaoxin, Tan Panlong, Gao Jie Research on measurement noise filtering method of ultrasonic flowmeter [J] Information and communication, 2016 (11)

[12] Kobayashi M, Jen C K, Bussiere J F, et al. High-temperature integrated and flexible ultrasonic transducers for nondestructive testing[J]. Ndt & E International, 2009, 42(2): 157-161

[13] Meng Tao, Wang Chi, Li Xiaopeng, Xing Chao, Wu Bo Comparison and analysis of measurement methods for flow stability [J] Instruments and equipment, 2018, 06 (02): 55-63

[14] Zhou Hongwei, Liu Desheng, Zu Haiyan Nonlinear compensation of eddy current sensor based on SVM inverse model [J] Sensors and Microsystems, 2009, 28 (7): 41-43

[15] Müller, U. Guidelines for the fluid mechanical validation of calibration test-benches in the framework of EN 1434