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Assembly process optimization of electromechanical meters based on robust design

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Abstract. The assembly precision of the magnetic system of an electromechanical meter is an important guarantee for the measurement accuracy of the meter. The large gap between the two poles of the magnetic system is the key point that affects the assembly precision and is also the difficulty that electromechanical meter manufacturers face. In this paper, the controllable factors that affect the gap of a magnetic system are selected by performing an orthogonal experiment, the assembly process is analyzed, and the noise factors are selected; the orthogonal design achieved by using inner and outer array is used to design the experiment scheme, and the optimal combination of process parameters with a large signal-noise ratio (SNR) and good robustness is found through the experiment. Through experimental verification, the improved process capability index reaches 1.34, and the optimization effect is remarkable.

Keywords: Magnetic system assembly of meters / robustness / orthogonal experiment / signal-noise ratio

1 Introduction

An electromechanical meter is an indispensable measuring tool in all walks of life and even in residents' lives, and the assembly of a magnetic system is the most critical process in the whole meter manufacturing process. The precision of the magnetic system greatly affects the metering accuracy of the electromechanical meter, and the working effect of the magnetic system directly affects the quality level and service life of the meter [1]. At present, whether the assembly of a magnetic system is qualified or not is mainly determined by measuring the gap tolerance. The gap tolerance of a magnetic system is one of the main reasons for the unqualified precision of electromechanical meters and has become an urgent problem for enterprises to solve. Scholars at home and abroad have performed much research on the characteristics of meters themselves, but there are few studies on the assembly process of meters. In reference [2], the assembly process of a magnetic system is analyzed by experimental design and process capability, and the optimum parameter combination is found by the Design of Experiment method. However, only one factor was analyzed in the experimental design without considering the interaction between the factors and the influence of uncontrollable factors. In reference [3], the six-sigma management DMAIC process is used to solve the gap over tolerance problem in the assembly process of meter magnetic systems, but the process is complex and costly.

In the manufacturing process of products, there are many controllable and uncontrollable factors that affect the stability of output characteristics [4,5], and it is difficult to completely eliminate the influence of these factors. The robust design method considers all kinds of parameter changes that may occur in the manufacturing process and makes the quality of the final product insensitive to changes in disturbance factors by adjusting the design [6,7]. The basic tool of this method is an orthogonal array, takes the signal-to-noise ratio (SNR) as the index to measure the stability of product quality, and uses cheap components to assemble products with reliable performance, low cost, and high stability [8,9]. Robust design can improve the anti-interference ability of products in process design. It has been widely used in electronics, machinery, the chemical industry, automobiles, etc. [10–15]. In reference [16], robust design is used to optimize two types of assembly processes: assembly based on the characteristics of component coordination and assembly based on the plate and shell components positioned by fixtures to improve the assembly quality of products. Reference [17] takes the sidewall of a high-speed train as the research object, establishes the influence relationship model between the fixture factor of the sidewall and assembly deviation, proposes the robust design method of assembly fixtures oriented to the quality stability of the sidewall, and realizes the optimization

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design of fixture positioning schemes. Reference [18] takes the assembly process of automobile taillight brackets as an example and proposes a robust design method for a compliant assembly process based on a support vector regression model, which improves assembly quality. In this paper, based on the principle of the robust design method, controllable factors are determined through orthogonal experiments, and the influence degree of controllable factors on assembly under the fluctuation of noise factors is analyzed. Finally, the optimal process conditions for the assembly process of an electromechanical meter are determined, which greatly reduces the large dispersion problem encountered in the assembly process of meters.

2 Brief introduction to the assembly process of the magnetic system of a meter

2.1 Basic composition of a magnetic system

In the manufacturing process of meters, the assembly of magnetic systems is the core process, and the assembly precision of magnetic systems guarantees the quality of meters. The base frame, the voltage assembly and the current assembly need to be positioned accurately. The final assembly tolerance requirement is (2.65±0.1) mm. Figure 1 is a physical drawing of some components and fixtures of the magnetic system. Figure 2 shows the tolerance requirements of magnetic system clearance after assembly.

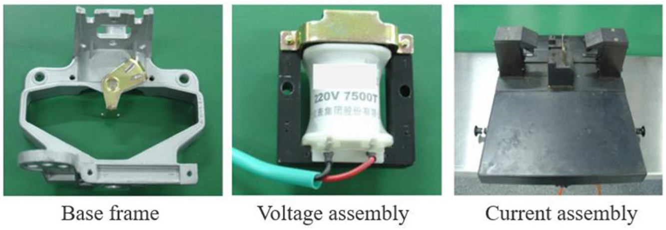

Fig. 1. Magnetic system components and fixtures.

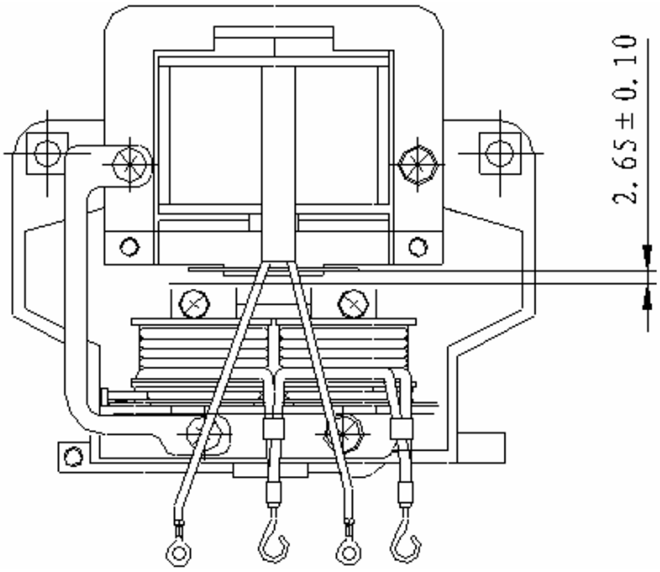

Fig. 2. Tolerance requirements for magnetic system clearances after assembly.

2.2 Assembly process flow of a magnetic system

The process steps for assembling a magnetic system are as follows. First, the operator places the base frame according to the operation instruction. Second, the air pressure of the fixture is adjusted to a fixed value to make the fixture clamp the base frame to ensure that there are no loose components in the assembly process. Then, the base frame, voltage assembly, current assembly, and screws are installed in sequence. After all components are in place, the screws are tightened using a pneumatic screwdriver. Finally, the assembly clearance of the magnetic system is checked. The assembly process of the magnetic system is shown in Figure 3.

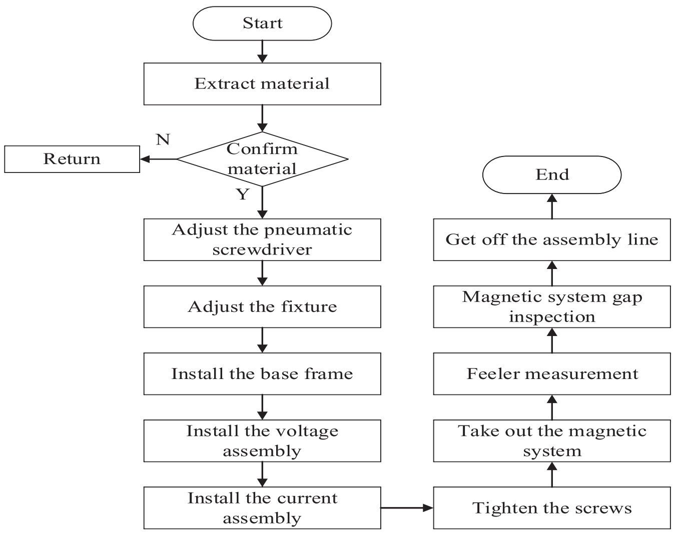

Fig. 3. Assembly flow chart of a magnetic system.

3 Robust design steps

This paper divides robust design into four stages:
(1) Prepare for the experiment

1. Determine the quality characteristics and objective function, appropriately select the controllable factors and their optional levels, and design the orthogonal experiment table and data analysis scheme.

The quality characteristic is the desired quality characteristic, the gap value of the magnetic system is selected as the quality characteristic, and its target value l is $l = 2.65 \pm 0.10$ (mm). Let y_{ij} be the magnetic system gap measured with the fluctuation of the jth noise factor combination for the ith process parameter combination. The goal of performing gap optimization on the magnetic system is to minimize the variance of the mean value at the target value. A scale factor can be found, which can move the mean value of the adjustment factor to the target value.

The maximum SNR is the objective function:

$$\eta \quad \frac{=10\,lg\,\overline{y}^2}{s^2} = 10lg\frac{\left(\frac{1}{i\,\times\,j}\sum_{i=1}\sum_{j=1}y_{ij}\right)^2}{\frac{1}{i\,\times\,j-1}\sum_{i=1}\sum_{j=1}\left(y_{ij}-\overline{y}\right)^2} \tag{1}$$

2. Analyze all noise factors that affect the qualification rate of the magnetic system assembly process and select the primary and secondary noise factors. At the same time, determine the experiment scheme for estimating the quality loss and reduce the sensitivity to the noise factor to the minimum.

(2) Carry out the experiment

The observation data of quality characteristic under different level combinations of various factors are obtained through experiment.

(3) Analyze data

1. Summarize the data obtained from each test, estimate the influence of controllable factors on quality characteristic, and calculate the SNR.

2. Comprehensively balance various factors, select the most appropriate level for each factor to obtain the best conditions, and finally, estimate the SNR according to the best conditions.

(4) Perform the verification experiment

Perform the verification test on the magnetic system assembly of the meter under the optimum conditions.

The technical route used for the robust design of the assembly process of the meter magnetic system is shown in Figure 4.

4 Analysis of factors influencing the assembly process of magnetic systems

4.1 Fishbone diagram

All the factors that may affect the assembly precision of the magnetic system are analyzed from the following aspects: the operator, the operating equipment, the assembling workpiece, the assembly method, and the operating environment. The following factors are listed, resulting in a fishbone diagram, as shown in Figure 5.

4.2 Screening of controllable factors

The main factors are analyzed and explained as follows.

(1) Inner diameter of the screw thread of the base frame

The inspection standard used for the inner diameter of the screw thread of the base frame is 3.459 ± 0.1 (mm). The inner diameters of the screw thread of the base frame are 3.359 mm, 3.459 mm, and 3.559 mm.

(2) Fixture air pressure

The air pressure is maintained at 22 psi during assembly of the production line, and the screw size is M4*20. The fixture air pressure is changed by adjusting the knob of the fixture air pressure valve instrument, and three levels of fixture air pressure are taken: 15 psi, 18 psi and 20 psi.

(3) Speed of a pneumatic screwdriver

The gear of a pneumatic screwdriver determines its rotational speed, and the rotating speed of a screwdriver takes three levels: low-grade 1, middle-grade 2, and high-grade 3.

(4) Screw assembly sequence

For the screw assembly sequence, three levels are taken: clockwise, cross, and counterclockwise, as shown in Figure 6.

(5) Fixture fixing deviation

The fixture fixing deviation is set to three levels: forward, fixed, and backward.

(6) Extraction mode

The extraction mode is set to three levels: vertical extraction, forward tilt extraction and backward tilt extraction.

An orthogonal experimental design [19] was used to analyze and determine the significant factors in the inner diameter of the screw thread of the base frame, the pressure of the fixture, the speed of the pneumatic screwdriver, the screw assembly sequence, the fixture fixing deviation and the extraction mode. Through the analysis of the above factors and levels, it was determined that there were 6 factors of 3 levels in this orthogonal experiment. Therefore, an $L_{27}(3^{13})$ orthogonal array was chosen to carry out the experiment. An orthogonal experiment was carried out according to the orthogonal array, and the measurement results were obtained as shown in Table 1.

Through mean range analysis of the measured data in Table 1 by Minitab 19 software, the main effect diagram of the mean shown in Figure 7 and the response table of the mean shown in Table 2 are obtained.

The effect diagram shows how each factor affects the response characteristics. The main effect exists when different levels of factors have different effects on characteristics. Main effect is the difference between the maximum and minimum average response values for each factor and is used to represent the relative effect of each factor on the response. Figure 7 and Table 2 show the extent to which each factor affects the gap in the magnetic system: speed of pneumatic screwdriver > fixture air pressure > inner diameter of the screw thread of the base frame > fixture fixing deviation > extraction mode > screw assembly sequence. Therefore, four factors such as the speed of the pneumatic screwdriver, fixture air pressure, inner diameter of the screw thread of the base frame and fixture fixing deviation are selected as controllable factors.

The speed of the pneumatic screwdriver, fixture air pressure, inner diameter of the screw thread of the base frame and fixture fixing deviation have a significant impact on the assembly precision of the magnetic system, which needs to be improved as process parameters in the subsequent robust design.

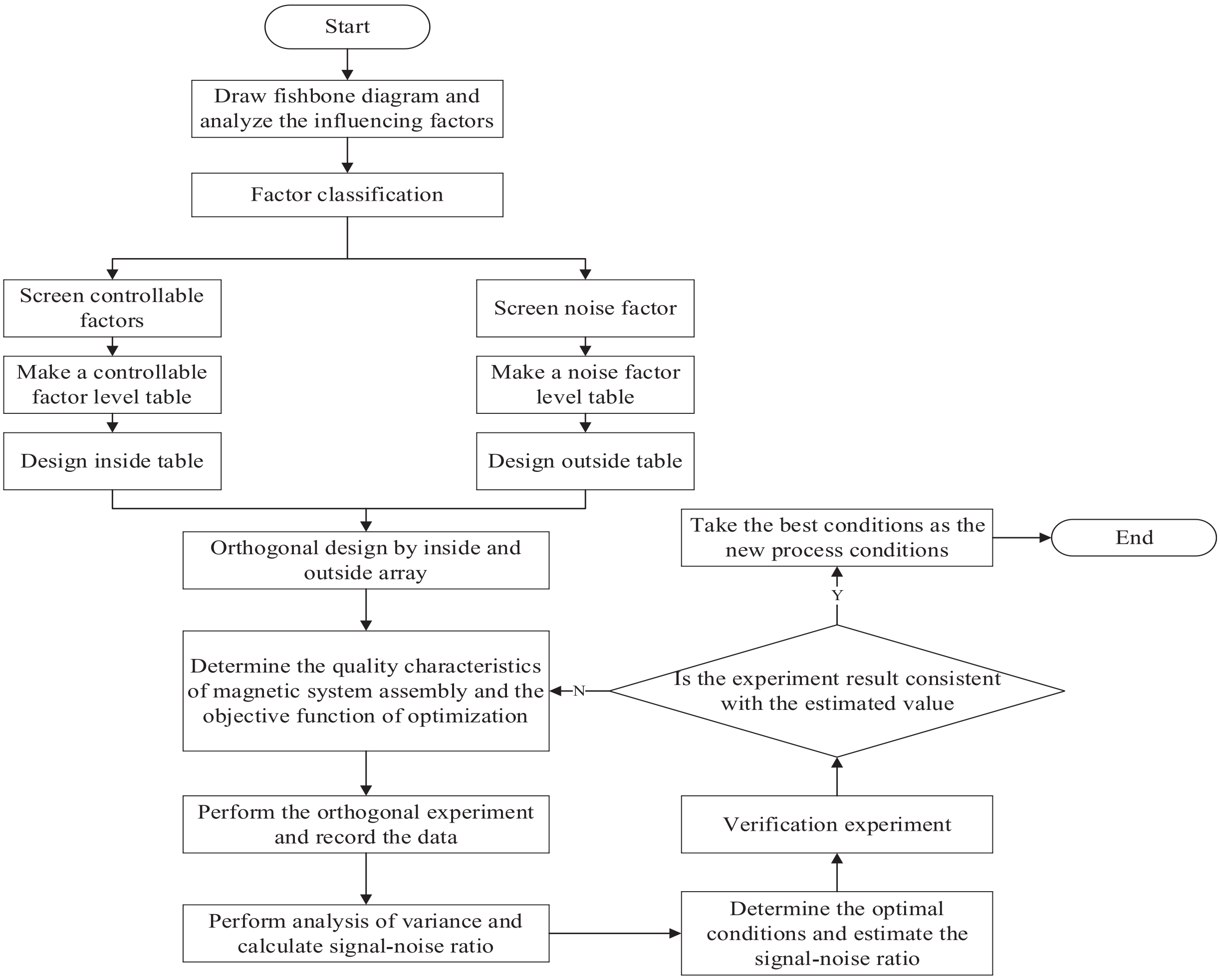

Fig. 4. Technical route used for robust design.

4.3 Screening of noise factors

By analyzing the assembly process of the magnetic system of an electricity meter, noise factors are obtained, such as the gap tolerance between the magnetic shunt and central pole surface, the degree of fixture fixation and the pressure fluctuation of the fixture.

– The geometric parameters of the voltage assembly affect the assembly quality, and the gap tolerance between the magnetic shunt and the pole surface is also a key factor affecting the precision of the magnetic system. The standard for the inspection of voltage assemblies is 2.25 ± 0.05 (mm). The present inspection standard is as follows: Is the feeler gauge accumulative thickness 2.20 mm~2.30 mm? Are voltage assemblies larger than 2.30 mm unacceptable? Since the quality of the voltage assembly is not controllable in the parameter design stage, it is impossible to determine whether the change in its geometric parameters has a significant impact on the magnetic system assembly. Therefore, the gap tolerance between the magnetic shunt and central pole surface is regarded as the noise factor, 2.20 mm~2.25 mmand 2.25 mm~2.30mm are taken as two different levels.

– The degree of fixture fixation has an impact on the gap of the magnetic system during assembly. Through field investigation and experiments, due to inevitable equipment wear, some fixtures will become loose after adjustment. Therefore, the degree of fixture fixation is also taken as a noise factor, “stable” and “loose” are taken as two different levels.

– Before assembly begins, the assembler adjusts and fixes the air pressure of the fixture. However, in practice, the air pressure will fluctuate by ± 1 psi, which will affect the accuracy of the air pressure and the assembly process. Therefore, the pressure fluctuation of the fixture is taken as the noise factor, and two different levels of -1 psi and $+1$ psi are taken.

5 Robust design of the magnetic system assembly process

5.1 Orthogonal design by the inner and outer array

Orthogonal design by inner and outer array is a kind of experimental design. It is different from the simple orthogonal experiment table in that it is from two orthogonal arrays arranged vertically to investigate the combined effect of one factor on the impact of another group of factors [20]. The factors are divided into two categories: controllable factors and noise factors. If they are put into different orthogonal array, the orthogonal array

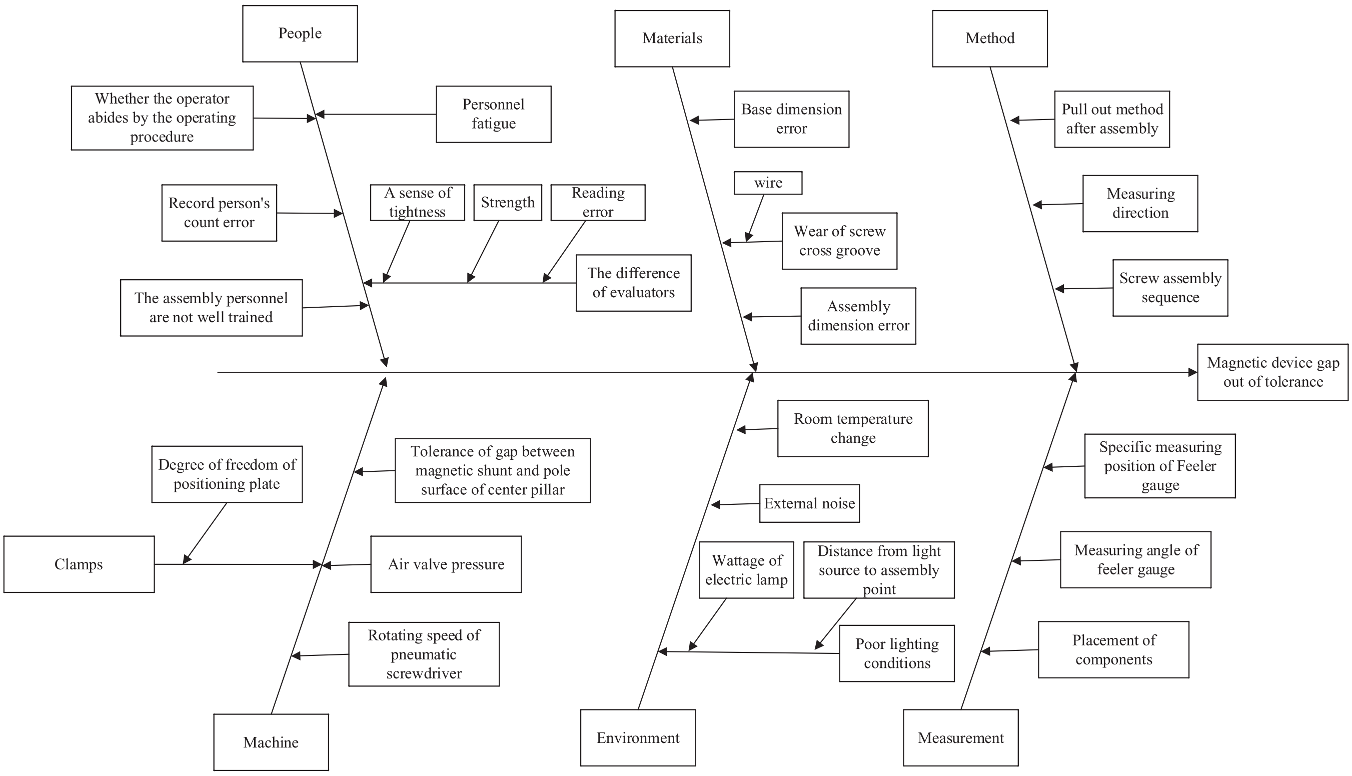

Fig. 5. Fishbone diagram of the magnetic system gap out of tolerance.

Table 1. Measurement results of controlled factor screening.

	Screw assembly sequence	Inner diameter of screw thread of base frame (mm)	Fixture air pressure	Fixture fixing deviation	Extraction mode	Speed of pneumatic screwdriver	Measurement results (mm)
1	clockwise	3.359	15	forward	vertical	1	2.58
2	clockwise	3.359	15	forward	forward tilt	2	2.56
3	clockwise	3.359	15	forward	backward tilt	3	2.55
4	clockwise	3.459	18	fixed	vertical	1	2.52
5	clockwise	3.459	18	fixed	forward tilt	2	2.57
6	clockwise	3.459	18	fixed	backward tilt	3	2.69
7	clockwise	3.559	20	backward	vertical	1	2.57
8	clockwise	3.559	20	backward	forward tilt	2	2.67
9	clockwise	3.559	20	backward	backward tilt	3	2.66
10	cross	3.359	18	backward	vertical	2	2.59
11	cross	3.359	18	backward	forward tilt	3	2.56
12	cross	3.359	18	backward	backward tilt	1	2.66
13	cross	3.459	20	forward	vertical	2	2.65
14	cross	3.459	20	forward	forward tilt	3	2.65
15	cross	3.459	20	forward	backward tilt	1	2.56
16	cross	3.559	15	fixed	vertical	2	2.56
17	cross	3.559	15	fixed	forward tilt	3	2.63
18	cross	3.559	15	fixed	backward tilt	1	2.54
19	counterclockwise	3.359	20	fixed	vertical	3	2.57
20	counterclockwise	3.359	20	fixed	forward tilt	1	2.57
21	counterclockwise	3.359	20	fixed	backward tilt	2	2.59
22	counterclockwise	3.459	15	backward	vertical	3	2.6
23	counterclockwise	3.459	15	backward	forward tilt	1	2.59
24	counterclockwise	3.459	15	backward	backward tilt	2	2.56
25	counterclockwise	3.559	18	forward	vertical	3	2.66
26	counterclockwise	3.559	18	forward	forward tilt	1	2.65
27	counterclockwise	3.559	18	forward	backward tilt	2	2.58

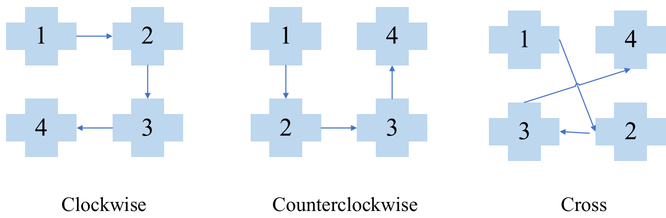

Fig. 6. Assembly sequence diagram of screws.

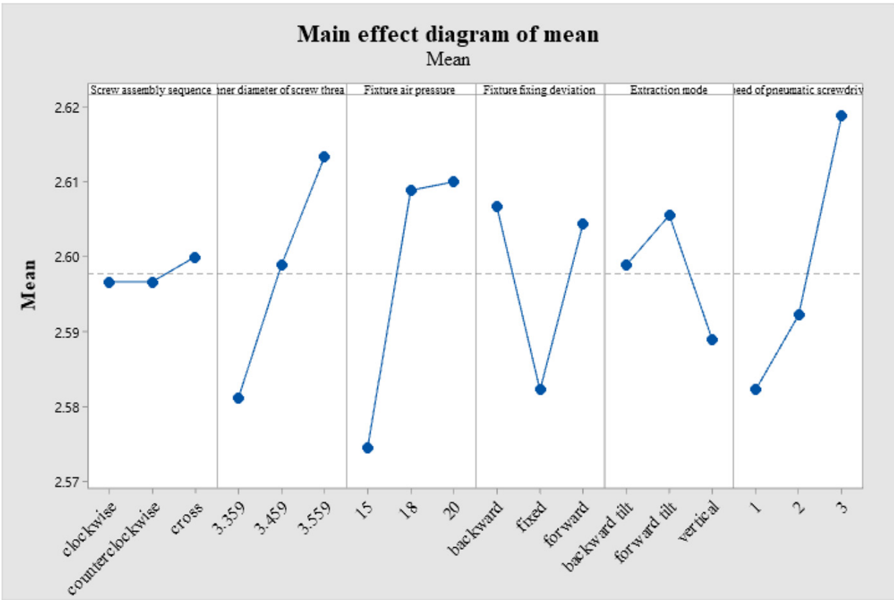

Fig. 7 Main effect diagram of the mean.

containing controllable factors are called inner array. The orthogonal array containing the noise factor is called the outer array, and then, the inner and outer array are arranged vertically to form a direct product table.

The speed of the pneumatic screwdriver, fixture air pressure, inner diameter of the screw thread of the base frame and fixture fixing deviation are all controllable factors at three levels. The controllable factor is suitable for the orthogonal array with four factors and three levels, so an $L_9(3^4)$ orthogonal array is used to design the inner array, as shown in Table 3.

The gap tolerance between the magnetic shunt and central pole surface, the degree of fixture fixation and the pressure fluctuation of the fixture are all two-level noise factors suitable for three-factor and two-level orthogonal array, so the use of $L_4(2^3)$ orthogonal array for the design of outer array is shown in Table 4.

Thus, the test plan under the orthogonal design by inner and outer array is obtained, and 36 assembly and measurement tests are carried out according to the plan. Each measurement is repeated three times, and the average value is taken to obtain the test data, as shown in Table 5.

5.2 Analysis of test data

The first step in data analysis is to summarize the data from each test and perform a numerical analysis accordingly. The data in Table 5 were analyzed by Minitab 19 software, and the values of the mean, SNR and standard deviation are shown in Table 6.

The second step of data analysis is to estimate the effect of each controllable factor on the quality characteristic in the presence of noise factor fluctuations. The average SNR of each factor at different levels is shown in Table 7, and the SNR main effect diagram is shown in Figure 8.

As seen from Figure 8, when the noise factor fluctuates in the magnetic system assembly, the four controllable factors all affect the SNR, but the difference is large. The

Table 2. Response table of the mean.

Level	Screw assembly sequence	Inner diameter of the screw thread of the base frame	Fixture air pressure	Fixture fixing deviation	Extraction mode	Speed of the pneumatic screwdriver
1	2.597	2.581	2.574	2.604	2.589	2.582
2	2.600	2.599	2.609	2.582	2.606	2.592
3	2.597	2.613	2.610	2.607	2.599	2.619
Main effect	0.003	0.032	0.036	0.024	0.017	0.037
Rank	6	3	2	4	5	1

Table 3. Inner array design.

Number	Inner diameter of the screw thread of the base frame (mm)	Fixture air pressure (psi)	Fixture fixing deviation	Speed of the pneumatic screwdriver
	A	**B**	**C**	**D**
1	1 (3.359)	1 (15)	1 (Forward)	1 (1)
2	1	2 (18)	2 (Fixed)	2 (2)
3	1	3 (20)	3 (Backward)	3 (3)
4	2 (3.459)	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3 (3.559)	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 4. Outer array design.

Number	Gap tolerance between the magnetic shunt and the central pole surface (mm)	Degree of fixture fixation	Pressure fluctuation of the fixture (psi)
	D	**E**	**F**
1	1 (2.20–2.25)	1 (Stable)	1 (–1)
2	1	2 (Loose)	2 (1)
3	2 (2.25–2.30)	1	2
4	2	2	1

variation in SNR caused by the inner diameter of the screw thread of the base frame is the largest, and the influence of fixture fixing deviation and fixture air pressure is the second largest. The change in SNR caused by the speed of the pneumatic screwdriver is the smallest, and the change range is much smaller than the change in SNR caused by the inner diameter of the screw thread of the base frame and fixture fixing deviation. The larger the SNR is, the better the controllable factor levels are: the inner diameter of the screw thread of the base frame is 3.359 mm, the fixture air pressure is 18 psi, the fixture fixing deviation is fixed, and the pneumatic screwdriver speed is second grade.

According to Table 7, the best level combination of significant factors affecting the gap of the magnetic system is $A_1B_2C_2D_2$. The SNR estimate is expressed as follows:

$$\hat{\eta}_0 = \overline{\eta} + \hat{a}_1 + \hat{b}_2 + \hat{c}_1 + \hat{d}_2 \tag{2}$$

Table 5. Test table under the orthogonal design by inner and outer array.

Outer array				E (mm)	2.20–2.25	2.20–2.25	2.25–2.30	2.25–2.30
				F	Stable	Loose	Stable	Loose
				G (psi)	−1	1	1	−1
Inner array				Number (j)	1	2	3	4
Number (i)	A (mm)	B (psi)	C	D	Y_1	Y_2	Y_3	Y_4
1	3.359	15	Forward	1	2.66	2.56	2.57	2.59
2	3.359	18	Fixed	2	2.59	2.56	2.59	2.56
3	3.359	20	Backward	3	2.56	2.63	2.6	2.66
4	3.459	15	Fixed	3	2.66	2.54	2.59	2.65
5	3.459	18	Backward	1	2.65	2.57	2.56	2.69
6	3.459	20	Forward	2	2.65	2.57	2.66	2.57
7	3.559	15	Backward	2	2.56	2.59	2.65	2.67
8	3.559	18	Forward	3	2.56	2.6	2.58	2.66
9	3.559	20	Fixed	1	2.63	2.57	2.55	2.59

Table 6. Mean, SNR and standard deviation.

Inner array test number	Outer array test number				Mean	Standard Deviation	SNR
	1	2	3	4			
1	2.66	2.56	2.57	2.59	2.595	0.045	35.201
2	2.59	2.56	2.59	2.56	2.575	0.017	43.444
3	2.56	2.63	2.6	2.66	2.613	0.043	35.729
4	2.66	2.54	2.59	2.65	2.610	0.056	33.373
5	2.65	2.57	2.56	2.69	2.618	0.063	32.383
6	2.65	2.57	2.66	2.57	2.613	0.049	34.494
7	2.56	2.59	2.65	2.67	2.618	0.051	34.166
8	2.56	2.6	2.58	2.66	2.600	0.043	35.589
9	2.63	2.57	2.55	2.59	2.585	0.034	37.580

Table 7. Average SNR under different levels of each factor.

Level	A	B	C	D
1	38.12	34.25	35.09	35.05
2	33.42	37.14	38.13	37.37
3	35.78	35.93	34.09	34.90

Table 8. Verification experiment results.

Quality characteristic		Prediction	Verification experiment result
Magnetic system gap	Value	/	2.64
	SNR	43.44	42.23

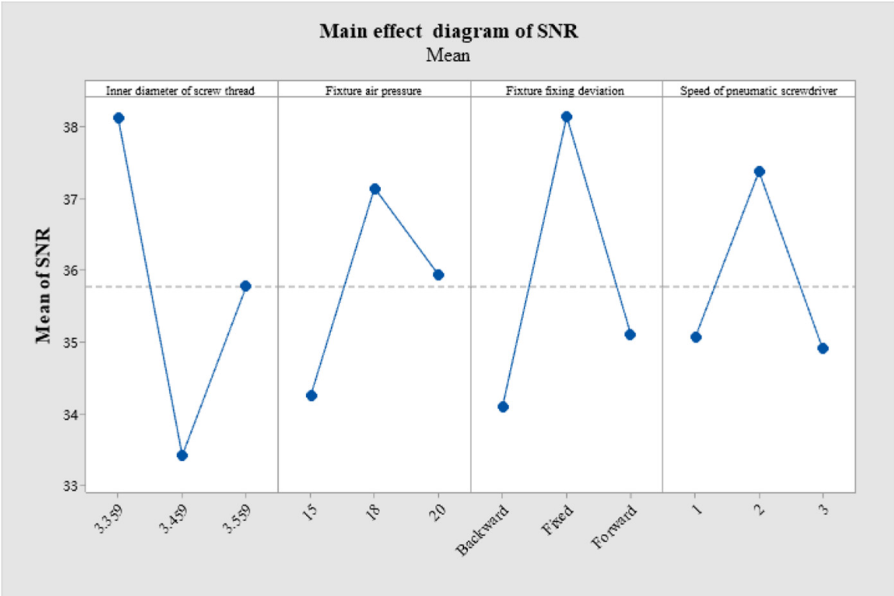

Fig. 8 Main effect diagram of the SNR of each factor.

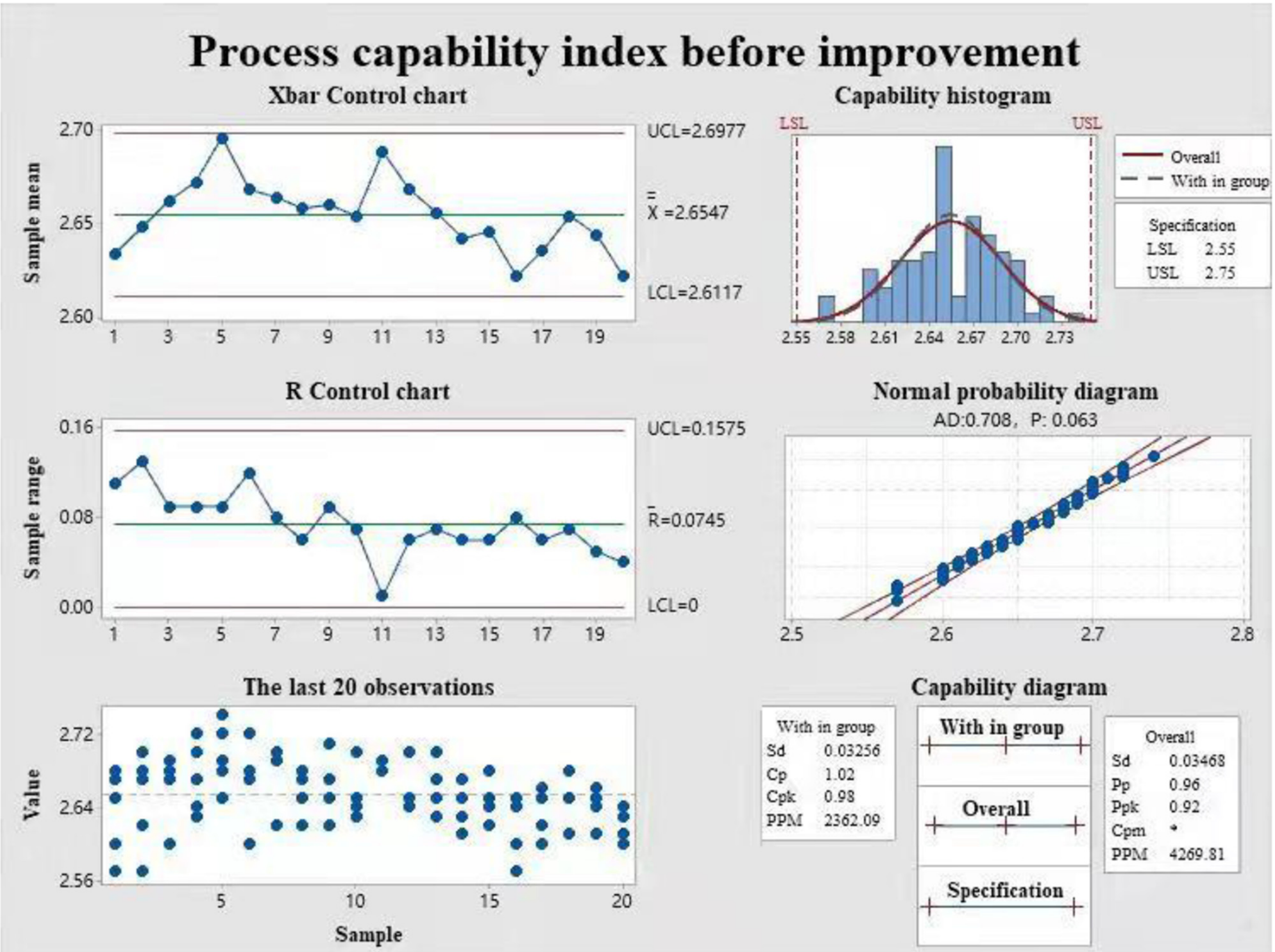

Fig. 9. Process capability index before improvement.

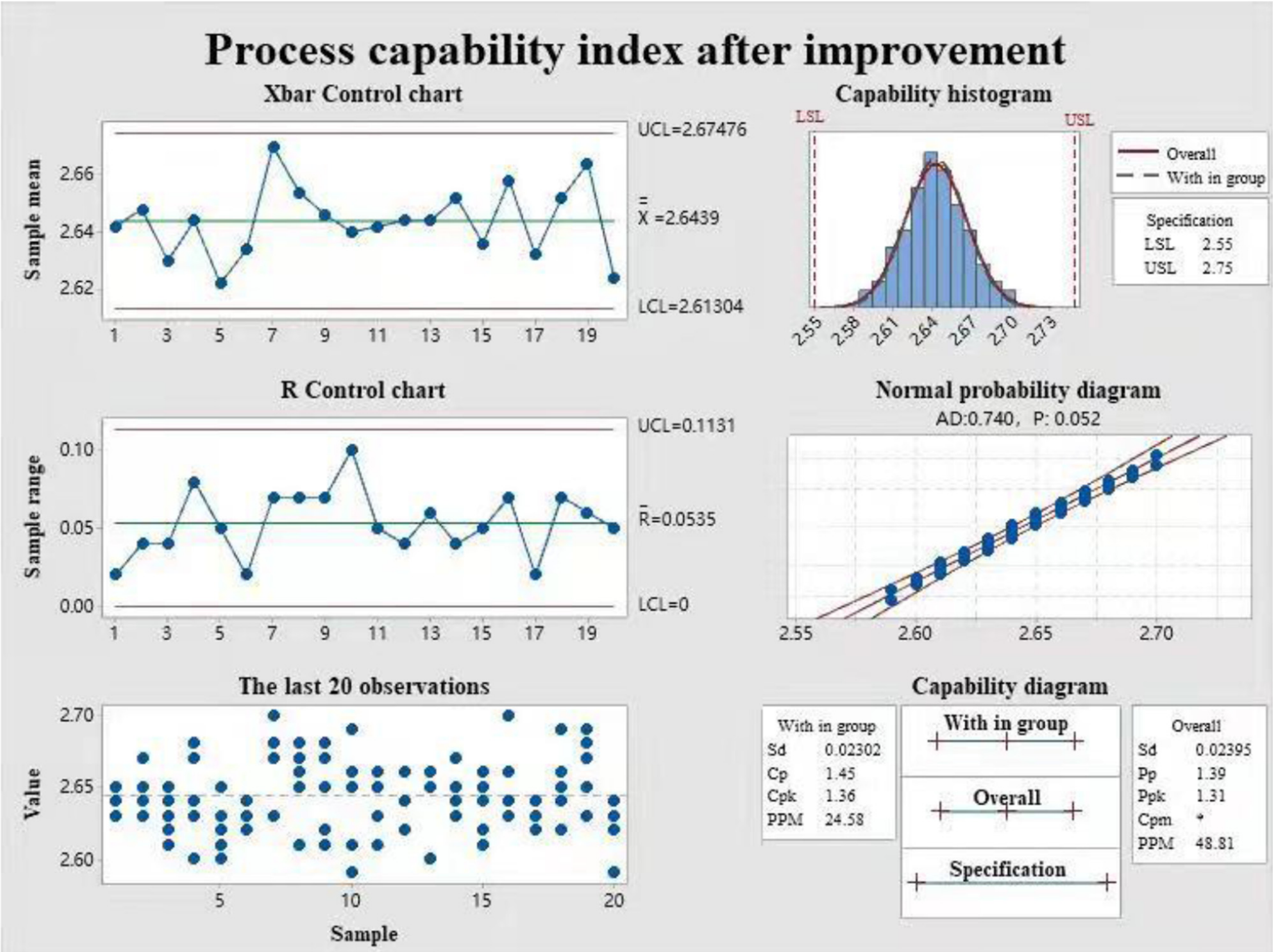

Fig. 10. Process capability index after improvement.

$$\begin{aligned}\hat{\eta}_0 &= \overline{\eta} + \left(\overline{A_1} - \overline{\eta}\right) + \left(\overline{B_2} - \overline{\eta}\right) + \left(\overline{C_1} - \overline{\eta}\right) + \left(\overline{D_2} - \overline{\eta}\right) \\ &= \overline{A_1} + \overline{B_2} +\end{aligned} \tag{3}$$

According to the data in Table 7,

$$\begin{aligned}\hat{\eta}_0 &= 38.12 + 37.14 + 38.13 + 37.37 - 3 \times 35.77 \\ &= 43.44(dB\end{aligned} \tag{4}$$

5.3 Verification experiment

For the magnetic system assembly of the meter, 20 groups of samples are selected for assembly according to the best process conditions, and the average value is taken after measuring the magnetic system gap. The experimental data are shown in Table 8.

The measured value of magnetic system gap after the improvement of assembly process is extracted for process capability analysis, and the results are compared with the process capability before improvement, as shown in Figures 9 and 10.

As seen from Table 8, the results of the verification experiment under the best conditions are in good agreement with the predicted values, and the gap values meet the specification requirements. As Figures 9 and 10 show the improved $C_{PK} = 1.36$ compared with the $C_{PK} = 0.98$ before improvement, the process capacity significantly improved. Therefore, the above optimum process conditions can be used as new process conditions.

6 Conclusion

Based on the robust design method, this paper determines the best process conditions for the assembly of the magnetic system of a meter and mainly achieves the following:

– In the robust design process, the key quality characteristic, optimization objective function and related factors were determined by drawing a fishbone diagram. The

controllable factors were screened by orthogonal experiment, and the noise factor and its level were further analyzed and determined.
– Then, the inner array and outer array were designed, and an orthogonal experiment was carried out under the orthogonal design by inner and outer array. The SNR of the obtained test data was calculated, and the impact was analyzed.
– Finally, the best combination of process parameters suitable for the magnetic system assembly of the meter was obtained, and its effectiveness was proven by a verification experiment. The gap process capability index of the improved magnetic system increased from 1.02 to 1.34.

The coupling relationship between noise factors is not considered in the selection of noise factors, so it is necessary to explore further from the actual assembly process.

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