A New Application of Taguchi Method: Matching and Optimization of Assembly Deviation of Mechanical System

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Abstract. In order to achieve high assembly accuracy on the basis of low manufacturing accuracy and low cost, a method of deviation factor matching and optimization based on Taguchi theory is proposed. Firstly, the specific process of multi factor matching and optimization is given based on Taguchi theory. Secondly, the orthogonal experiments were set from the aspects of performance index, influencing factors determination, orthogonal table selection and so on, and the best level combination of each deviation was selected to form the factor matching and optimization experiment scheme based on Taguchi method. Finally, taking the horizontal machining center as the object, the Taguchi method is used to match the deviation factors of each mating surface, and the best parameter combination of control factors is A₁B₂C₂D₁E₁, which verifies the effectiveness and practicability of Taguchi method. The research method in this study provides a strong support for the realization of high assembly accuracy and performance without increasing cost.

1. Introduction
The tolerance and assembly deformation deviation of each mating surface of mechanical products are continuously accumulated in the assembly system, which affects the assembly accuracy of subsequent assemblies, and eventually leads to the existence of unqualified products [1]. In the industrial production process, the workload of the product in the assembly process accounts for about 45% of the total amount of the whole product production cycle, and the proportion of the cost of the assembly process in the total cost of the product can reach 20-30% or even higher [2]. With the increasing degree of product internationalization, it has become the goal of enterprises to develop new products with high quality, low cost and short cycle. Therefore, on the basis of low manufacturing accuracy of parts, ensuring high assembly accuracy of products plays an important role in ensuring product quality.

How to produce high quality products with low cost has always been the most concerned problem of enterprises. For the research of tolerance allocation and robust optimization method, at present, it mainly focuses on the optimization criterion of the relationship between tolerance and cost and the solution method of optimization model. Alfredo et al. [3] proposed a processing cost tolerance relationship model based on the choice of equipment in the processing process. Jiang [4] took the coupling of manufacturing cost, testing cost and loss cost as the objective function of the model to build the optimization model of tolerance. Hsieh [5] combined process capability with product life cycle cost function to build tolerance cost optimization model. Kumar and Stalin [6] established the mathematical model of tolerance based on the lowest machining cost of parts, and obtained the tolerance value that meets the requirements through Lagrange multiplier method. Geetha et al. [7] established a tolerance optimization model...
including tolerance cost and quality loss cost to solve the tolerance optimization problem of assembly parts. Forouraghi [8] analyzed the tolerance optimization model of assembly, solved the mathematical model by using the multi-objective particle swarm optimization method, and obtained the optimal tolerance allocation combination.

In order to explain the relationship between product economic cost and quality, Dr. Taguchi proposed a quality engineering management method and concept, which is to promote the improvement of product quality from the manufacturing stage to the product design stage [9]. However, Taguchi method has not really been applied in practical production. Rao et al. [10] summarized Taguchi method, proposed detailed design steps and established that Taguchi method can be used as an effective tool for robust design. Kapoor et al. [11] gave the modified formulas for calculating the signal-to-noise ratio of the two kinds of target characteristics, fuzzy target and clear target, so as to be popularized in engineering practice. Lin and Wu [12] proposed a sea model design method based on Taguchi quality loss function. Giovagnoli and Roman [13] proposed an improved double response surface method, that is, robust design through simulation experiments. Debashree et al. [14] summarized the research on multi-objective optimization of surface roughness and maximum material removal rate, and proposed Taguchi method to obtain the optimal parameters. Krishnan [15] used Taguchi method to optimize the casting process parameters, and obtained the best combination of parameters, but there is a certain disparity between the results and the reality.

In summary, for the research of tolerance matching and optimization, most scholars mainly obtain the best scheme of tolerance allocation from the relationship between tolerance and cost of the optimization model, which has a certain deviation from the actual situation. In addition, Taguchi method is still in the conceptual stage, and has not been applied to mass production. In order to approach the actual working condition to the greatest extent, it is of great value to study the real deviation matching and optimization method based on Taguchi method for effectively improving product performance.

In order to achieve high assembly accuracy based on low manufacturing accuracy and low cost, this study presents an assembly error matching and optimization method based on Taguchi theory. Firstly, based on Taguchi theory, the specific process of multi factor matching and optimization is given; Secondly, the orthogonal experiments were set from the aspects of performance index and influencing factors determination, orthogonal table selection, etc. to form the experimental scheme of factor matching and optimization based on Taguchi method; Finally, taking the horizontal machining center as the object, Taguchi method is used to match the deviation factors of each fitting surface, which verifies the effectiveness and practicability of Taguchi method, and provides support for the realization of high assembly accuracy and performance of products without increasing cost.

2. Matching and optimization of parameters based on Taguchi theory

2.1. Theory of Taguchi method

Taguchi method is a quality engineering method with low cost and high efficiency, which emphasizes that the improvement of product quality is not achieved through inspection but through design. Its main process is as follows [16]: The orthogonal table is used to carry out grouping matching test, and the manufacturing error of each part is taken as the factor to make statistics and comparison of various test schemes at different levels, so as to obtain the best design scheme. On this basis, the reasonable matching among design parameters is completed with the assembly performance as the goal.

Taguchi method orthogonal array is to analyze the influence of various combinations of various factors on the quality, and then to obtain the best combination of factors based on the evaluation standard of signal-to-noise ratio (S/N). The quality characteristics of products into three categories [17]: ‘definite-purposed character’, ‘larger-the-better character’, ‘smaller-the-better character’.

Assume the quality characteristic value of the product, \( \eta \), is a random variable, its mathematical expectation is \( u \), variance is \( \sigma^2 \), then
$$\eta = \frac{u^2}{\sigma^2}$$  \hspace{1cm} (1)

For the purpose of product quality characteristics is to reach or approach the target value, the S/N of the desired characteristics can be obtained from Eq. (2):

$$\eta = \frac{S}{N} = -10 \log \left[ s^2 + (\overline{y} - m)^2 \right]$$  \hspace{1cm} (2)

where:

$$\overline{y} = \frac{1}{n} \sum_{i=1}^{n} y_i$$  \hspace{1cm} (3)

$$s^2 = \frac{1}{n-1} \sum_{i=1}^{n} (y_i - \overline{y})^2$$  \hspace{1cm} (4)

$m$ is the quality characteristic value.

Aiming at minimize and maximize the quality characteristics of products, the S/N is:

$$\eta = \frac{S}{N} \approx -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right)$$  \hspace{1cm} (5)

$$\eta = \frac{S}{N} \approx -10 \log \left( \frac{1}{n} \frac{1}{y_i^2} \right)$$  \hspace{1cm} (6)

where, $\overline{y}^2$ is the square of the mean error of the closed loop; $s^2$ is the variance of the error.

Taguchi method mainly aims at high quality, low cost and short cycle through experiments, and carries out different combinations of various factors, so as to achieve parameter optimization:

2.2. Determination of performance index and influencing factors
Orthogonal experiment is mainly used the orthogonal table as the analysis tool to match many factors that affect the performance of the target, and then obtain the optimal combination of parameters.
This study takes a horizontal machining center as the object, as shown in Figure 2.

![Figure 2. High precision horizontal machining center.](image)

Taguchi method is used to match the factors that affect the assembly accuracy. Firstly, the performance index and the influencing factors of the horizontal machining center are explained:

a) Test performance index

In this test, the spatial position of the centroid point of the cross section of the ram shaft hole of the horizontal machining center in the reference coordinate system is taken as the index. By matching and combining the deviation factors of each fitting surface which affect the end position of the system, a group of optimal parameter combination schemes are obtained by using certain evaluation criteria.

b) Test factors and level determination

According to the structure and working requirements of horizontal machining center, this section analyses the factors affecting the fitting surface deviation of the end position: the coupling deviation parameters of each fitting surface that affect the accuracy of the end system are taken as the relevant factors for the orthogonal test, and the deviation factors are divided into two groups, as shown in Fig.3.

![Figure 3. Schematic diagram of factor analysis.](image)

In order to improve the reliability of the analysis data, Monte Carlo simulation method is used to randomly select multiple samples within a certain normal distribution and deviation range as the factors affecting the performance index, and they are divided into two groups, level 1 and level 2 in turn, as shown in Table 1.
Table 1. The levels table of deviation factors.

| Deviation position | Bed | Slider 1 | Slipway | Slider 2 | Shaft hole |
|--------------------|-----|---------|---------|---------|------------|
| Level 1            | 1   | 1       | 1       | 1       | 1          |
| Level 2            | 2   | 2       | 2       | 2       | 2          |

According to the above analysis, $L_8(2^5)$ orthogonal table is selected for the experiment. The test scheme is shown in Table 2.

Table 2. The test scheme.

| Deviation position | Bed (A) | Slider 1 (B) | Slipway (C) | Slider 2 (D) | Shaft hole (E) |
|--------------------|---------|--------------|-------------|--------------|----------------|
| No. 1              | 1       | 1            | 1           | 1            | 1              |
| No. 2              | 1       | 1            | 1           | 2            | 2              |
| No. 3              | 1       | 2            | 2           | 1            | 1              |
| No. 4              | 1       | 2            | 2           | 2            | 2              |
| No. 5              | 2       | 1            | 2           | 1            | 2              |
| No. 6              | 2       | 1            | 2           | 2            | 1              |
| No. 7              | 2       | 2            | 1           | 1            | 2              |
| No. 8              | 2       | 2            | 1           | 2            | 1              |

3. Example analysis

This section takes the horizontal machining center as the test object. The objective is to minimize the deviation of the actual position of the end of the system from the ideal position. The Taguchi method was used to match the deviation factors of each mating surface, and the best matching scheme of each deviation factor was obtained. The experimental design process is shown in Fig. 4.

In this experiment, the closer the deviation from the ram center at the end of the system to the closed ring composed of the basic bed is, the better. Therefore, the S/N of the desired characteristics is used as the evaluation standard to determine the matching scheme of various factors. In order to ensure the accuracy of the test results, 5000 samples are randomly selected from the coupling deviation between...
the mating surfaces, and the mean value and variance of the closed-loop deviation of each grouping experiment are calculated. The calculation results are shown in Table 3.

| Number | Average error | Variance | S/N |
|--------|---------------|----------|-----|
| 1      | -14.6         | 0.057    | -23.3 |
| 2      | -7.3          | 0.049    | -17.3 |
| 3      | 0.0029        | 0.049    | 13.3  |
| 4      | -3.7          | 0.047    | -11.3 |
| 5      | -0.089        | 0.051    | 12.3  |
| 6      | 3.7           | 0.052    | -11.4 |
| 7      | 0.024         | 0.050    | 12.9  |
| 8      | 7.3           | 0.055    | -17.3 |
| Random combination | 0.132 | 0.093 | 9.4 |

It can be seen from table 3 that the variance and mean value of the No.3 group of experiments are small, and the S/N is large, which indicates that the third No.3 group experiments is the best combination in each group of matching experiments.

In order to verify the advantages and disadvantages of Taguchi method and ordinary random method in ensuring assembly accuracy, the deviation matching combination and random combination in the first group and the third group of Taguchi method orthogonal table are calculated respectively. Fig.5 shows the comparison of the spatial error distribution along the axis coordinate of the centroid point \( P_0 \) of the cross section of the axial hole of the ram calculated by the two methods in the reference coordinate system.

![Figure 5. Comparison of spatial deviation distribution of section centroid points: (a) The first group, (b) The third group](image)

As shown in Fig. 5, by comparing the test results of the first and third groups of orthogonal table matching and random combination, it is concluded that the spatial cumulative deviation range distribution of the third group of orthogonal table of Taguchi method is more concentrated, and the section centroid point tends to the ideal position. Therefore, the third group of orthogonal table of Taguchi method is determined as the optimal matching combination.

Through the analysis of the above evaluation methods, it can be seen that in the assembly of the horizontal machining center, the parameter combination of the best control factors is \( A_1B_2C_2D_1E_1 \), which can achieve a better effect of controlling the cumulative error, so as to reduce the manufacturing difficulty and cost, and improve the overall assembly quality and performance of mechanical products.

4. Conclusions

Group assembly is an optimization method to obtain high assembly accuracy without increasing manufacturing cost and machining accuracy. In this paper, the orthogonal table of Taguchi method is used as the basis of manufacturing error grouping experiment. Through the deviation matching control
experiment of different parts grouping, the optimal combination of various deviation factors is obtained. The main conclusions are as follows:

(1) Based on Taguchi theory, the specific process of multi deviation factor matching and optimization is given, which provides the basis for the subsequent grouping matching of deviation factors.

(2) The orthogonal experiment was set up from the aspects of experimental factors, level and orthogonal table, and the best level combination of each deviation was selected. The experimental scheme of factor matching and optimization based on Taguchi method was formed.

(3) Taking the horizontal machining center as the object, Taguchi method is used to match the deviation factors of each mating surface. The best parameter combination of control factors is \(A_1B_2C_2D_1E_1\), which verifies the effectiveness and practicability of Taguchi method.

The Taguchi method used in this paper can obtain the best matching and combination scheme among multi deviation factors, which provides method support for achieving high assembly accuracy and performance of products on the basis of low cost and low machining accuracy.

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