Precision Distribution of Turntable Gear Transmission System of Aero-engine Blade Processing Machine

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Abstract. In the previous design and research on the gear transmission error of the five-axis machine turntable, the selection of the five-axis machine tool turntable gears mainly uses the high-precision gears to avoid excessive transmission errors of the turntable, to meet the design requirements of the turntable. However, the cost of the turntable manufacturing is increased and it causes excess precision and unnecessary waste. In meeting the requirements of accuracy, it is important to distribute the gear transmission error of the turntable reasonably, to avoid the high manufacturing cost of the five-axis machine, improve the technical quality of the five-axis machine turntable and reduce its cost. This paper presented the self-developed five-axis machine turntable for aero-engine blade processing as the carrier, and the optimized genetic algorithm is used as the tool to allocate the precision of the gear transmission system. While to meet the design and use requirements, the gear accuracy level is reduced. The manufacturing cost of the turntable goes down.

Keywords: Turntable of blade processing machine; optimized genetic algorithm; precision distribution of transmission system.

1. Foreword
The theoretical basis of traditional precision allocation has been based on the principles and methods of determining precision allocation; For example, similarity principle (analogous method), equal tolerance principle, equal influence principle, proportional influence principle, equal precision principle, etc.[1] In short, any combination of error synthesis theory and any precision distribution principle is a method that can be applied to the gear transmission error of the five-axis machine turntable[2]. In fact, from the perspective of actual production, the above methods generally do not have a comprehensive, in-depth and detailed analysis of the functions and structural features of the parts, such as the size of the gear, the cumulative error of the tooth pitch, the axial run out error of the gear and the cost factors[3]. Therefore, the tolerances of the five-axis machine turntable gear transmission system determined according to the above-mentioned traditional precision distribution principle are generally adjusted, matched and repeatedly calculated according to the technical skill that hands on the experienced factory labors in
actual production. With the rapid development of computer technology, the development and popularization of mechanical optimization design has also entered the fast lane. The development direction of precision distribution is gradually moving towards optimized distribution.

1. Driving gear shaft  2. Helical gear  3. Intermediate gear shaft.
6. Output shaft helical gear  7. Thrust ball bearing  8. Slotted disc spring

**Figure 1.** Five-axis machine turntable gear transmission system
According to the analysis of the error of the five-axis machine tool turntable gear transmission system (the structure is shown in Figure 1) in *Aircraft engine Blade Processing Machine Turntable Pre-adjustment Angle Research* [4], a five-axis machine turntable is calculated by Monte Carlo method, the maximum value of the transmission system error, that is, the transmission error of the turntable transmission system unable to exceed this error value, and the maximum error value is used as the reference value for the distribution of the accuracy of the turntable transmission system. This paper uses genetic algorithms to establish the mathematical model of precision distribution optimization by determining the design variables, objective function and constraint conditions of the turntable transmission system. The multi-objective genetic algorithm is used to obtain the optimal solution of the precision distribution plan, and complete the turntable transmission system optimized design of precision distribution plan.

2. Precision distribution method

2.1. Brief Guide to the Genetic Algorithm

Genetic Algorithm (Genetic Algorithm) is a kind of random optimization search method that draws on the evolutionary law of survival of the fittest in the biological world [5]. The main feature is to do the direct operation on structural objects, with no limitation of derivation and function continuity. With inherent implicit parallelism and better global search capabilities, using probabilistic optimization methods, it can automatically obtain and guide the optimized search space, self-adapt and adjust the search direction without the definite rules. The properties of genetic algorithms have been used in different features such as combinatorial optimization, machine learning, signal processing, adaptive control, and artificial life. It is a key technology in modern intelligent computing [6].

2.1.1. Characteristics of Genetic Algorithm. The operation of genetic algorithm is simple and it is easy to learn. It consists of seven basic steps: coding, initial population generation, hybridization, fitness value evaluation and detection, selection, mutation, and termination. The genetic algorithm has the following four characteristics.

1) The initial stage of operating the genetic algorithm is to start the search from the set of problem solutions, not from the single. Traditional optimization algorithms iteratively find the optimal solution from a single initial value, which is easy to mislead into the local optimal solution. The genetic algorithm starts search from the string set, covers it comprehensively, which is conducive to global selection. At the same time, the algorithm itself is easy to realize the parallelization [7].

2) The genetic algorithm does not use the knowledge of search space or other auxiliary information. The individual has evaluated only by the fitness function value and performed the genetic operations. The fitness function is not only not restricted by continuous differentiability, but the domain from that function can be set arbitrarily. This feature expands the usage scale of genetic algorithms [8].

3) The genetic algorithm does not use the deterministic rules. The probabilistic change rules to guide his direction.

4) The genetic algorithm has self-organization and self-adaptive self-learning. When it is to automatically organize the search by using the information obtained from the evolutionary process, individuals with high adaptability have the high production probability and obtain a genetic structure that is more adapted to the environment [9].
2.2. Mathematical Modeling of Precision Distribution Optimization

2.2.1. Design Variables. Table 1 Accuracy distribution design variables

| variable | meaning |
|----------|---------|
| x1       | Comprehensive tangential error of gear 1 |
| x2       | Comprehensive tangential error of gear 2 |
| x3       | Comprehensive tangential error of gear 3 |
| x4       | Comprehensive tangential error of gear 4 |
| x5       | Clearance between the hole of gear 2 and the shaft |
| x6       | Clearance between the hole of the gear 4 and the shaft |
| x7       | The radial run out error of the journal of the installation of the gear 2 |
| x8       | The radial run out error of the journal of the installation of the gear 4 |
| x9       | Bearing radial clearance of gear 1 |
| x10      | Bearing radial clearance of gear 2 |
| x11      | Bearing radial clearance of gear 3 |
| x12      | Bearing radial clearance of gear 4 |

2.2.2. Constraints. The constraints of the design variables directly determine the accuracy of the optimization results. The value range of the variable is selected according to the different accuracy grades of the gears of the five-axis machine turntable gear transmission system. The accuracy grades are selected from 5 to 8. Then it refers to the Mechanical Design Manual for the gears of different accuracy levels to determine the tangential comprehensive error for each gear, the gap between the gear hole and the shaft, the radial runout error of the journal at the installation location and the radial clearance of the bearing. The value range is presented on Table 2. The unit of design variable is μm.

| design variable | Ranges      |
|-----------------|-------------|
| x1              | 20.5, 29.5, 42, 60 |
| x2              | 30.5, 44.5, 62, 88 |
| x3              | 29, 41, 58, 82 |
| x4              | 35, 50, 71, 99 |
| x5              | 25~40        |
| x6              | 25~40        |
| x7              | 7~21         |
| x8              | 7.5~21       |
| x9              | 5~10         |
| x10             | 5~10         |
| x11             | 5~10         |
| x12             | 5~10         |

According to the requirements of optimized design, the transmission error of the optimized five-axis machine turntable gear transmission system should be within the design error range. Based on the processing characteristics of the five-axis machine, the turntable must have large torque, fast response, high precision, and good wear resistance. The turntable adopts a high-torque servo motor, which is driven by a two-stage gear reduction to ensure the balance of large torque and high response. The gear reduction mechanism adopts a double-gear anti-backlash mechanism and a high-precision angle encoder to ensure the high rotation accuracy and repeat positioning accuracy of the turntable. According to the
main specifications of the five-axis machine tool provided by engineers and technicians: rated speed \( n = 60 \text{r/min} \), turntable output rated power \( P = 8.5 \text{Kw} \), positioning accuracy 16", repeat positioning accuracy 12", rotation angle 360°, The limit rotation diameter of the A-axis (turntable) is 300mm. The positioning accuracy of the turntable is 15". The operation system adopted by the turntable is the SINUMERIK-840D CNC system, it is used in various machines. Since the five-axis machine uses a closed-loop servo control system, it is compared with open-loop servo control. The positioning accuracy of the system is an order of magnitude higher. Therefore, the positioning error of the mechanical transmission part of the five-axis machine turntable is 10 times of the design error, which is less than or equal to 150". When a five-axis machine is processing parts, the thermal error of the machine is one of the main factors affecting the machining accuracy of the machine. It accounts for 40% to 70% of the overall error. The method of separating and modeling thermal errors is adopted. After error compensation, the compensation rate can reach 60%. Finally, the proportion of thermal errors in the overall error of the machine is 16% to 28%. After excluding the influence of thermal error, the allowable value of the design error of the five-axis machine tool turntable is 108 to 126.

From the previous paper *Study on the Pre-adjustment Angle of the Turntable of Aero-engine Blade Processing Machine*, the design error formula of the gear transmission system is:

\[
\Delta \theta = \frac{\Delta \theta_1}{i_2} + \Delta \theta_2
\]

From the perspective of security and stability, the overall gear transmission error after optimization is less than the allowable value of the design error, and the optimization goal is obtained based on the design variables should meet the error constraints:

\[
\Delta \theta = \frac{\Delta \theta_1}{i_2} + \Delta \theta_2 \leq 108
\]

2.2.3. *Objective Function.* In the genetic algorithm, the selection of the objective function directly affects the performance of the optimization model. The optimization result obtained by a single objective function is not often the optimal solution, and the optimization result has one-sidedness and limitations. Therefore, in the solution of actual problems. Generally, according to relevant specific conditions, multiple objective functions are selected for optimal solution. According to the characteristics of gear transmission, the cost objective function, equilibrium objective function and robust objective function are selected respectively. A new fitness function is formed by these three objective functions, and finally the transformed fitness function is solved by the steps of genetic algorithm.

(1) *Cost Objective Function*

For the five-axis machine tool turntable, the manufacturing cost is directly related to the sales volume of the machine tool, and it also reflects the success of the machine tool design from the side. On the basis of satisfying the production and processing of machine, it is very important to reduce the production cost as much as possible in the early design process. For the transmission error distribution of the five-axis machine tool turntable transmission system studied in this paper, the gears with different accuracy levels inside the system have a great impact on the manufacturing cost of the turntable. Within the tolerance range of the turntable design, the higher the precision level of the gear, the higher the manufacturing cost, vice versa. One of the key points of this paper is to select gears with lower accuracy levels as possible to meet the requirements of the turntable design and achieve the design accuracy of the turntable transmission system and reduce the production cost.

In the multi-index evaluation system, due to the different nature of each evaluation index, they usually have different dimensions and orders of magnitude. When the levels of various indicators are very different, if the original indicator values are directly used for analysis, the role of indicators with higher values in the comprehensive analysis will be highlighted, and the role of indicators with lower numerical levels will be relatively weakened. Therefore, in order to ensure the reliability of the results, it is necessary to standardize the original index data. The design variables need to be normalized to avoid distortion. After linear transformation of the original data, the formula is as follows:

\[
\]
Therefore, the formula of the cost objective function is as follows:

\[ f_1(x_i(i)) = \max \sum_{i=1}^{12} x_i(i)^2 \]

(2) Balance Objective Function

In the precision distribution of the five-axis machine turntable gear transmission system. It should be avoided that one error value is very low and another one is high. In addition, because the gear error value has the characteristic of discrete type, the axial run-out error and radial run-out error of the corresponding gear are equalized, and the equalization objective function is:

\[ X_{i}\left( i \right) = \min \left[ X_{i}(1), X_{i}(2), X_{i}(3), \cdots X_{i}(12) \right] - \{ \min \left[ X_{i}(1), X_{i}(2), X_{i}(3), \cdots X_{i}(12) \right] \}^2 \]

(3) Robust Objective Function

As we all know, the design requirements of any product cannot fully meet the ideal state of the product due to various factors in actual production. This is also unavoidable for the turntable gear transmission system of a five-axis machine tool. In order to maximize the stability of the error of the gear transmission chain of the turntable. Measures can be taken to reduce the uncertainty of the error value of the design variables, and the robust objective function is designed based on the sensitivity analysis. The value of the robust objective function is:

\[ f_3(x_i(i)) = \min \left[ \sum_{i=1}^{12} \left[ \frac{\partial \Delta \theta_{\text{max}}}{\partial x(i)} \Delta x(i) \right] \right] \]

(4) Fitness Function

The fitness function is the optimal value optimization of the constrained linear equation based on the minimum value. According to the design requirements, the maximum transmission error value of the turntable gear transmission system after the precision distribution should be less than the design error of the turntable. Convert the above three objective functions into the following form:

\[ F_1(x_i(i)) = 40 - \sum_{i=1}^{12} k_i \cdot x_i(i)^2 \]

\[ F_2(x_i(i)) = (\max [x_i(1), x_i(2) \cdots x_i(12)]) - (\min [x_i(1), x_i(2) \cdots x_i(12)])^2 \]

\[ F_3(x_i(i)) = \sum_{i=1}^{12} \left[ \frac{\partial \Delta \theta_{\text{max}}}{\partial x(i)} \Delta x(i) \right] \]

Use weighting method. After discussing with the engineering staff, the weighting coefficients of the cost objective function, the equilibrium objective function and the robust objective function are determined to be respectively. The new fitness function is:

\[ F(x) = \sum_{m=1}^{3} c_m \left( \frac{F_m - F_{m}^\Delta}{F_m^4} \right)^2 \]

Since what is required is that the maximum value of the transmission error of the turntable gear after the accuracy distribution is less than the error design value, but the fitness function defaults to the minimum value of the transmission error of the turntable, so it is necessary to add a minus sign to the fitness function and convert Get the maximum transmission error after the precision distribution. That is, the function obtained by the genetic algorithm is:

\[ f(x) = - \sum_{m=1}^{3} c_m \left( \frac{F_m - F_{m}^\Delta}{F_m^4} \right)^2 \]

The constraints satisfied are:

\[ \Delta \theta_{st} = \frac{\Delta E_1 + \Delta E_2 \ast Z_3}{r_2} \ast Z_4 + \frac{\Delta E_3 + \Delta E_4}{r_4} \leq 2.25 \]
3. Accuracy Distribution Calculation

According to the above analysis, using matlab to write a genetic algorithm program to get the result of
the precision distribution of the turntable gear transmission system, the genetic algorithm has a crossover
probability of 0.7, a mutation probability of 0.3, evolution times 500, and a population size of 500.
According to the previous constraints, the optimization results of the five-axis machine tool turntable
gear system are finally obtained after calculation as shown in Table 3:

| Table 3. High-precision distribution plan |
|-------------------------------------------|
| parameter                                | Optimized solution | Level 5 accuracy |
| Comprehensive tangential error of gear 1 X1 | 30.40             | 20.5             |
| Comprehensive tangential error of gear 2 X2 | 47.11             | 30.5             |
| Comprehensive tangential error of gear 3 X3 | 58.20             | 29               |
| Comprehensive tangential error of gear 4 X4 | 72.19             | 35               |
| Clearance between the hole of gear 2 and the shaft X5 | 25.23             | 27               |
| Clearance between the hole of gear 4 and the shaft X6 | 26.30             | 21               |
| The radial run out error of the journal of the installation of the gear2 | 8.02              | 7.2              |
| The radial run out error of the journal of the installation of the gear4 X8 | 8.06              | 7.5              |
| Bearing radial clearance of gear 1 X9 | 6.51              | 5                |
| Bearing radial clearance of gear 2 X10 | 8.91              | 5                |
| Bearing radial clearance of gear 3 X11 | 7.39              | 5                |
| Bearing radial clearance of gear 4 X12 | 8.34              | 5                |

According to the turntable gear transmission error formula, the optimized design parameters are
taken into account. The maximum transmission error after accuracy optimization is 104.62", which is
less than the allowable design transmission error range of the turntable gear transmission system design,
which meets the design requirements and the precision distribution is reasonable. From optimization
results, it can be concluded that: the selection of the comprehensive tangential errors of gear 1, gear 2,
gear 3 and gear 4 can be appropriately increased, the gap between the hole and the shaft does not change
much, and the journal radial runout error at the installation location can be appropriately increased . The
bearing radial clearance has no obvious change. In comprehensive consideration, after consulting the
mechanical design manual according to the tangential comprehensive error of the gear, the gears of the
gear system of the five-axis machine tool turntable are reselected. According to the symmetry of the
gear structure, the optimized The gear accuracy grade changes are shown in Table 4:

| Table 4. Comparison of gear accuracy before and after optimization |
|---------------------------------------------------------------------|
| Gear 1                  | Accuracy level before optimization | Optimized accuracy level |
| Gear 2                  | 5                                    | 6                        |
| Gear 3                  | 5                                    | 7                        |
| Gear 4                  | 5                                    | 7                        |
| Gear 5                  | 5                                    | 7                        |
| Gear 6                  | 5                                    | 6                        |

From the optimized gear accuracy grade table, it presents that under the premise of meeting the
design error requirements, the accuracy grade of each gear has been reduced, reaching the initial
optimization design goal, and reducing the manufacturing cost of the turntable of the five-axis machine.
It also reduces the production cost of a five-axis machine as a whole, avoids excess precision, and increases market competitiveness. Considering the price of different precision grades such as the material and size of the gear, the cost price of the gear before optimization is 100 CNY, but the optimized one is 60 CNY, which shows considerable benefits for mass production.

4. Summary
The precision distribution of the gear transmission system of the five-axis machine turntable is a complicated theme. This study analyzes the influencing factors of gear transmission error, and uses probability statistics to solve the transmission error of the turntable according to the randomness of the error. Under the condition of meeting the design error of the turntable, the common problem of excess precision in the manufacturing and installation of the turntable is solved. Set the minimum cost as the objective function, the genetic algorithm is used to reasonably allocate the transmission error of the turntable. After doing the optimization, the gear cost is reduced 40%, from 100 CNY to 60 CNY. This result not only meets the design requirements of the turntable, but also effectively avoids excess precision.

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References
[1] Sheng Hongliang, Yang Wenyun. The development direction and key of modern mechanism precision distribution theory[J].Optical Technology,1990(05):33-36.
[2] Wang Xing, Zhao Changjian, Liang Zhuo, et al. Accuracy optimization allocation method of anti-ship missile mid-guided inertial unit based on multi-objective genetic algorithm[J].Aerospace Control,2018,36(03):9-14.
[3] Wang Tao, Li Hang. Accuracy analysis and design of machine tool based on error prediction [J].Manufacturing Technology and Machine Tool, 2019(11):125-129.
[4] Xiong Fengkui, Liu Kang, Xu Yun, et al. Study on the pre-adjustment angle of the turntable of Hangfa blade processing machine tool[J].Modular Machine Tool and Automatic Processing Technology,2019(08):26-28+52.
[5] Xu Li, Liu Yunhua, Wang Qifu. Application of adaptive genetic algorithm in robot path planning [J].Computer Engineering and Applications, 2020, 56 (18):36-41
[6] Zhang Yuzhou, Xu Tingzheng, Zheng Junshuai. Solving emergency logistics problem with uncertain urgency based on hybrid genetic algorithm [J].System Science and Mathematics, 2020, 40(04):714-728.
[7] Ma Yongjie, Yun Wenxia. Research progress of genetic algorithm [J].Application Research of Computers, 2012, 29(04):1201-1206+1210.
[8] Ge Jike, Qiu Yuhui, Wu Chunming, Pu Guolin. Summary of genetic algorithm research [J].Application Research of Computers, 2008(10): 2911-2916.
[9] Xi Yugen, Chai Tianyou, Yun Weimin. Summary of Genetic Algorithms [J].Control Theory and Applications, 1996(06): 697-708.