Design and evaluation of module configuration scheme for special machine tool of variable hyperbolic circular-arc-tooth-trace cylindrical gear

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Abstract
In the design and evaluation process of the module configuration for the special machine tool of variable hyperbolic circular-arc-tooth-trace cylindrical gear, the similar coefficient of each module attribute is calculated by using fuzzy mathematics theory, and the closest module is retrieved, so as to obtain the module configuration design scheme set. It is difficult to judge the influence degree of different evaluation factors precisely because of the strong fuzziness of many evaluation factors. Using the improved set pair analysis theory to analyze the uncertainty and fuzziness of the evaluation factors of the machine tool module configuration scheme, fuzzy linguistic values are constructed for evaluation factors and transformed into triangular fuzzy numbers, thus the evaluation decision matrix is established. At the identity time, the entropy weight method is used to determine the factor weight to improve the objectivity of the scheme optimization. The IDO (identical different opposite) relation degree between the module configuration scheme and the most ideal scheme is established. The scheme closeness degree is introduced to sort the alternative schemes, and the comprehensive evaluation decision-making model is established to realize the optimization of the machine tool module configuration design scheme and obtain the optimal configuration design scheme.

Keywords
Module configuration, module retrieval, evaluation and optimization, set pair analysis, triangular fuzzy entropy weight method, variable hyperbolic circular-arc-tooth-trace cylindrical gear

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Introduction
Variable hyperbolic circular-arc-tooth-trace cylindrical gear is a new type of gear pair which can meet the requirements of heavy load and high precision. In the direction of tooth width, the tooth-trace is a space arc and tooth profile of the middle section is an involute curve, the other sections are the envelope curve of hyperbolic family with uniform variation. Compared with helical gear, variable hyperbolic circular-arc-tooth-trace cylindrical gear has no axial thrust and is

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insensitive to installation error. Compared with herringbone gear, there is no relief groove and continuous process can be realized. Variable hyperbolic circular-arc-tooth-trace cylindrical gear transmission has the advantages of good meshing performance, large coincidence coefficient, large bearing capacity, high transmission efficiency, no additional axial force, long service life, high stability and low noise.

At present, many innovative achievements are manufactured mostly by advanced multi-axis CNC machine tools in the manufacturing industry. Therefore, the research of advanced CNC machine tools in China has made great achievements. Advanced CNC machine tools have great advantages for single and small batch processing, most complex parts can be manufactured, thus providing equipment guarantee for the innovation of manufacturing industry. However, there are some problems when using advanced CNC machine tools to process this new type of gear as the basic parts: firstly, its poor economy and high processing cost are one of the bottlenecks of large-scale industrial application of this kind of basic parts; Secondly, when processing these basic parts many functions are in the redundant state; Moreover, for this new type of gear transmission, there are principle errors because advanced CNC machine tool processing is a typical approximate processing, mainly using interpolation for the corresponding manufacturing. This new type of gear adopts the meshing principle to carry out the corresponding mathematical modeling and derivation, and uses the corresponding spatial relationship to design the special machine tool, which can effectively avoid this kind of principle error. Therefore, special machine tools can effectively reduce the redundancy of machine tools, to greatly reduce the processing cost, and improve the processing accuracy and efficiency.

Due to the particularity of gear geometry, processing theory and manufacturing system are not yet. Special processing equipment is deficient, large-scale application in the industrial field is restricted. Therefore, the research and development of special machine tool for variable hyperbolic circular-arc-tooth-trace cylindrical gear is urgent. In the modular design of the gear special machine tool, the design and evaluation and optimization of the machine tool module configuration scheme is a difficult problem.

The concept of configuration design was first proposed by Freeman and Newell in 1971. According to the different ways of knowledge expression and reasoning mechanism, scholars in China and abroad had carried out research on product configuration design. Ostrosi and Tié Bi et al. extracted the impact of configuration requirements based on instance output and proposed a model hierarchy based on hierarchy structure to solve the optimization. Hvam et al. proposed a configuration system based on module division theory and established a product modular structure for configuration. Jianrong et al. gave the information model of product configuration template and configuration solution strategy. Hui et al. realized the configuration process through constraint based configuration rules.

The module configuration design has the characteristics of multiple solutions. It is necessary to evaluate the advantages and disadvantages of the configuration scheme and choose it reasonably after the configuration design is completed. The evaluation and optimization of module configuration scheme is a multi-objective comprehensive decision-making problem. Multi attribute scheme evaluation is generally divided into three stages: decision information aggregation, attribute weight solution, scheme sorting and optimal scheme selection. At present, the commonly used system scheme evaluation methods in China and abroad are basically summarized as follows: analytic hierarchy process, fuzzy comprehensive evaluation method, gray comprehensive evaluation method, matter element analysis method, cluster analysis method, and neural network method.

Kulak et al., applied information axiom to multi-attribute decision-making system, quantitatively described the fuzzy needs of customers through fuzzy theory and realized the calculation method of fuzzy information. Ayag provided a design evaluation method based on analytic hierarchy process (AHP) and simulation analysis. Si et al. under the framework of AHP, integrated Delphi method and fuzzy theory to complete the decision-making of design scheme in subjective environment. Azimifard et al. provided solutions to the supplier selection problems faced by supply chain managers combined with AHP and TOPSIS. Chen and Huang proposed a multi-attribute evaluation method based on IVIFVs and linear programming. Among them, the attribute weight and the attribute evaluation value are represented by IVIFN, and the weight of the attribute is effectively solved by linear programming. Xin-zhao and Fang quantified qualitative evaluation factor information that is difficult to calculate through fuzzy mathematics theory and considered the influence of coupling degree on the evaluation of the scheme. Ren et al. established the evaluation model of configuration scheme based on neural network technology, and compared and sorted the configuration scheme sets. Wang et al. established a decision model of comprehensive evaluation of configuration scheme based on Analytic hierarchy process entropy weighted gray correlation method. Song and Ming proposed the optimal solution of the integrated rough set theory to determine the configuration scheme. Li et al. proposed a method for the evaluation of complex product module division scheme based on mixed fuzzy multi-attribute decision theory. Although more and more scholars have applied various
Module configuration scheme design

The design process of machine tool configuration scheme is essentially the process of retrieving, combining and optimizing the modules in the machine tool module instance library to form products that meet the personalized requirements of customers. It is an effective means of rapid product design according to customer needs. The specific steps and processes are as follows: the process is shown in figure 1.

Step 1: customer demand is the original starting point and driving force for enterprises to design and produce various products. Through the analysis of customer demand information, the technical characteristic factors required for product configuration are formed.

Step 2: compare the machine tool product case library to find the product model consistent with the customer demand expression. If there are products that fully meet the customer’s needs in the instance library, enter step 6; Otherwise, the modules need to be retrieved and matched one by one.

Step 3: retrieve the module library. If there are modules that fully meet the needs of customers, enter step 5; Otherwise, the module needs to be optimized, modified or innovated to meet the configuration requirements.

Step 4: store the modified module in the module library to expand and update the module library of the product and provide more instance choices for future retrieval.

Step 5: based on configuring constraint rules, combine and replace the modules that meet the design requirements to form a new product structure tree and add it to the machine tool product instance library.

Step 6: generate a machine tool module configuration scheme set that meets customer requirements.

In step 3, the specific process of the machine tool module retrieval algorithm is as follows:

1. The module retrieval is divided into qualitative attribute retrieval and quantitative attribute retrieval. After the module qualitative attribute retrieval, there are x modules in the module library whose qualitative attributes meet the matching conditions, and the set of quantitative attributes of these modules is \( A = \{ A_1, A_2, A_3, \ldots, A_x \} \), set \( M_0 \) is the target module target module for customer needs.

2. Normalize the quantitative attributes in the target module and the retrieved module.

Suppose for a quantitative attribute \( A_j \) in the module. The quantitative attribute values of each module in the module library are: \( A_{j1}, A_{j2}, \ldots, A_{jx} \), the qualitative attribute value of the target module is \( A_{j0} \) normalization formula is as follows:

\[
\Delta_j = |A_{j1} - A_{j0}|, \quad \Delta_{j2} = |A_{j2} - A_{j0}|, \quad \ldots, \quad \Delta_{jx} = |A_{jx} - A_{j0}|
\]

\[
\Delta_j = \max\{\Delta_{j1}, \Delta_{j2}, \ldots, \Delta_{jx}\} \tag{1}
\]

3. Calculate the similarity coefficient of each quantitative attribute \( S_{ji} \), the formula is as follows:

\[
S_{ji} = \frac{\Delta_i}{\Delta_j}, \quad i \in [1, x] \tag{2}
\]

Obviously, The smaller the value \( S_{ji} \), the greater the similarity between the quantitative attribute of this module and the quantitative attribute of the target module. Then repeat the above calculation process for other quantitative attributes of the module.

4. The similarity between each module instance and the target module is calculated as follows:

\[
S_j = \sum_{i=1}^{x} \sum_{j=1}^{y} S_{ji} \omega_j \quad \sum_{j=1}^{y} \omega_j = 1 \tag{3}
\]

Where, \( j \) is the number of quantitative attributes of each module in the module library, \( S_j \) is the similarity coefficient corresponding to each quantitative attribute, \( \omega_j \) is the weight of each quantitative attribute given by the designer or expert. With minimum \( S_j \) with the module \( M \) is the module most similar to the target module of customer requirements (the module with the best variant basis).
Evaluation optimization of configuration scheme

Because the evaluation of configuration scheme involves a lot of machine tool performance and user needs, the evaluation of evaluation factors often has strong fuzziness and uncertainty, which makes the evaluation process of configuration scheme very complex. In order to reduce the subjective influence of the fuzziness of each evaluation factor on the configuration scheme evaluation, this paper takes the special machine tool for variable hyperbolic circular-arc-tooth-trace cylindrical gear as the research object, the evaluation factors of module configuration scheme are transformed into triangle fuzzy numbers and quantified reasonably. Combined with entropy weight method, the weights of each evaluation factor in the module configuration scheme are scientifically revised. The fuzzy comprehensive evaluation method based on set pair analysis is used to sort and select the best scheme set, and the best configuration scheme is obtained, which enhances the objectivity and effectiveness, and provides a new decision-making method for the evaluation of module configuration scheme of complex products. The evaluation process of configuration scheme is shown in Figure 2.

Triangular fuzzy numbers of evaluation factor

The evaluation factor of module configuration scheme has uncertainty and fuzziness. Fuzzy language is the value of qualitative attribute factor, which cannot be directly calculated with quantitative factor. In order to reduce the subjective uncertainty in the decision-making process, it is necessary to quantify the qualitative criteria of the evaluation scheme. Li et al.21 introduced the theory of fuzzy set in the process of quantifying the qualitative factors, and transformed the simple evaluation semantics into the corresponding interval number and fuzzy number. Zhang et al.22 used interval intuitive fuzzy number to describe fuzzy evaluation semantics in the process of edge weight assignment, so as to avoid the subjective uncertainty caused by different professional level of designers.

Language factors are generally expressed as grade 5 to grade 9 evaluation factors.23,24 This paper adopts seven fuzzy language factors, \( v = \{ \text{very poor, poor, middle lower, middle, middle upper, good, very good} \} \) as the seven level language evaluation set, in which: very poor < poor < middle lower < middle < middle upper < good < very good. Triangular fuzzy number is a method to transform fuzzy and uncertain linguistic variables into definite values. Using triangular fuzzy number in the evaluation method can solve the contradiction that the performance of the evaluated object cannot be accurately measured and can only be evaluated by natural language. In this paper, the fuzzy language evaluation factor of the module is transformed into triangular fuzzy number, and the triangular fuzzy number is normalized by using the multi factors statistical analysis method,25 and the normalized fuzzy factors are obtained, as shown in Table 1.

The triangle fuzzy number \( a = (a_l, a_m, a_u) \) is defined as the fuzzy information of expert judgment to describe the uncertainty of expert evaluation. The triangle fuzzy number \( (a_l, a_m, a_u) \) represents the deviation degree from the mean value \( a_m \). \( a_l \) and \( a_u \) respectively represent the most pessimistic, probable and optimistic estimates of experts, among which \( a_l \) is the lower bound and \( a_u \) is the upper bound. The center of area (COA) is used to make the fuzzy number real. The best non fuzzy performance value (BNP) of the fuzzy comprehensive evaluation value is calculated by the formula:
BNP_{ij} = \left[ (a_{ij}^u - a_{ij}^l) + (a_{ij}^m - a_{ij}^l) \right] / 3 + a_{ij}^m \quad (5)

In the above,

\begin{align*}
  a_{ij}^m &= (1/q) \odot (a_{ij}^{m_1} \oplus a_{ij}^{m_2} \oplus \cdots \oplus a_{ij}^{m_q}), \\
  i &= 1, 2, \cdots, m, \quad j = 1, 2, \cdots, n 
\end{align*} \quad (6)

In equations (5) and (6), $a_{ij}^{m_q}$ is the fuzzy comprehensive evaluation values of the evaluation factor $j$ for $i$ candidate configuration schemes by $q$ experts; $\odot$ and $\oplus$ are multiplication and addition operations of fuzzy numbers.

**Entropy weight method to determine the weight of evaluation factor**

Weight is used to measure the importance of each factor of the system relative to the whole system.\(^{26}\) Entropy weight method is an objective weighting method, which is mainly based on the discrete degree of the data itself. Compared with those subjective valuation methods, it has higher accuracy and objectivity, and can better explain the results. Entropy weight method is a data processing method to determine the objective weight according to the variability of factors.

There are $m$ machine tool module configuration schemes and $n$ evaluation factors. The fuzzy comprehensive value of the evaluation factors is obtained by formulas (5) and (6). For the $j$ evaluation factor value of the $i$ configuration scheme, the values of each configuration scheme on the identity evaluation factor are not necessarily the identity, and there are maximum and minimum values. Therefore, for each data, the standardized value is

\begin{equation}
  Y_{ij} = \frac{x_{ij} - x_{ij}^{\min}}{x_{ij}^{\max} - x_{ij}^{\min}} \quad (7)
\end{equation}

According to the definition of information entropy in information theory, the entropy of evaluation factor is defined as:

**Figure 2.** Evaluation flow chart of machine tool module configuration scheme.

**Table 1.** Standardization of fuzzy language factor of level 7.

| Number | Fuzzy language factor | Triangular fuzzy number | Normalized fuzzy number |
|--------|-----------------------|-------------------------|-------------------------|
| 1      | very good             | (10, 12, 12)            | (0.833, 1.000, 1.000)   |
| 2      | good                  | (8, 10, 12)             | (0.667, 0.833, 1.000)   |
| 3      | middle upper          | (6, 8, 10)              | (0.500, 0.667, 0.833)   |
| 4      | middle                | (4, 6, 8)               | (0.333, 0.500, 0.667)   |
| 5      | middle lower          | (2, 4, 6)               | (0.167, 0.333, 0.500)   |
| 6      | poor                  | (0, 2, 4)               | (0, 0.167, 0.333)       |
| 7      | very poor             | (0, 0, 2)               | (0, 0, 0.167)           |
Among them, $p_{ij} = Y_{ij}/\sum_{i=1}^{m} Y_{ij}$. When $p_{ij} = 0$, then \( \lim_{p_{ij} \to 0} p_{ij} = 0 \). According to formula (8), \( 0 \leq E_j \leq 1 \).

If $p_{ij} = 1/m$, then $E_j = 1$. In a word, the more consistent $p_{ij}$ it is, the closer $E_j$ it is to 1, so it is not easy to distinguish the advantages and disadvantages of configuration schemes.

Define the discrimination of evaluation factor to configuration scheme

$$F_j = 1 - E_j$$

(9)

The weight calculation formula of evaluation factor is as follows:

$$\omega_j = \frac{F_j}{\sum_{j=1}^{n} F_j}, j = 1, 2, \cdots, n$$

(10)

**Set pair analysis and module configuration scheme evaluation method**

Set pair analysis theory is a mathematical theory proposed by Professor Zhao Keqin in 1989 to study system certainty and uncertainty. The basis is the connection number of connection mathematics,\(^{27}\) which is a systematic mathematical analysis of the certainty and uncertainty of two sets in set pair and the interaction between certainty and uncertainty under certain background. It can effectively solve the random, fuzzy and other uncertainties,\(^{28}\) and make the evaluation results more objective.

Set up a set of machine tool module configuration schemes $S = (S_1, S_2, \cdots, S_m)$ to meet the customer’s needs, and aim at the ideal optimal scheme $S_0$. For the set pair $H = (S_k, S_0)$ formed by any scheme $S_k$ and the ideal optimal scheme $S_0$, analyze the identity, difference and opposition of the set sum in the set pair $S_k$ and $S_0$ and establish the identity different opposite (IDO)

$$\mu_k = a_k + b_k i + c_k j = \sum_{i=1}^{n} \omega_i a_k^i + \left( \sum_{i=1}^{n} \omega_i b_k^i \right) i + \left( \sum_{i=1}^{n} \omega_i c_k^i \right) j$$

(11)

Where $\omega_i$ is the weight of evaluation factor $i$, which is calculated by equation (10). $a_k + b_k + c_k = 1$, $a_k$ is the identity degree, $c_k$ is the opposite degree, $j$ is the opposite identification coefficient, usually take $-1$, $b_k$ is the difference degree, $i$ is the difference coefficient, according to the specific situation in $(-1,1)$ interval value. In fact, there is a certain part in it, that is, there

is a part belonging to the identity degree or the difference degree. The uncertainty $b_k$ is analyzed and the determined part is stripped out to further improve the accuracy and reliability of the evaluation.

Decompose the $b_k$, $b_k = b_k(a_k + b_k + c_k) = a_k b_k + b_k b_k + b_k c_k$, and put the separated $a_k b_k$ into the identity degree and $b_k c_k$ into the opposite degree. So equation (11) can be improved as follows:

$$\mu_k = a_k^i + b_k^i i + c_k^i j = a_k + a_k b_k + b_k b_k i + (c_k + b_k c_k) j$$

$$\mu_k = \sum_{i=1}^{n} \omega_i a_k^i \left( 1 + \sum_{i=1}^{n} \omega_i b_k^i \right) i + \sum_{i=1}^{n} \omega_i c_k^i \left( 1 + \sum_{i=1}^{n} \omega_i b_k^i \right) j$$

(12)

The mathematical model of scheme closeness degree is introduced, and the mathematical model of optimal configuration scheme is obtained as follows:

$$M = \frac{a_k^i}{a_k^i + c_k^i}$$

$$M = \frac{\sum_{i=1}^{n} \omega_i a_k^i \left( 1 + \sum_{i=1}^{n} \omega_i b_k^i \right)}{\sum_{i=1}^{n} \omega_i a_k^i \left( 1 + \sum_{i=1}^{n} \omega_i b_k^i \right) + \sum_{i=1}^{n} \omega_i c_k^i \left( 1 + \sum_{i=1}^{n} \omega_i b_k^i \right)}$$

(13)

The above mathematical model indicates the relative closeness between the scheme $S_k$ and the optimal scheme $S_0$. The larger the $M$ is, the closer the design scheme is to the optimal scheme. The final design scheme can be chosen according to the size of $M$.

**Evaluation optimization of module configuration scheme for special machine tool of variable hyperbolic circular-arc-tooth-trace cylindrical gear**

In order to realize the rapid customization of special machine tool for variable hyperbolic circular-arc-tooth-trace cylindrical gear, this kind of special machine tool is pitched into modules, and each module has different types and models of sub modules to choose from. As shown in Figure 3:

As there are many kinds of modules, according to the needs of customers, the module is selected and matched according to the specific selection and constraint rules. After module retrieval and module configuration sequence solution, three module configuration schemes are obtained:

Scheme $S_1$: large cutter disk, main shaft box, gear blank clamper, gear pitch mechanism, X-direction
NC slide, Y-direction NC slide, Z-direction NC slide, body, upright column, foundation, protection cover, numerical control device, electrical control system, hydraulic system, pneumatic system, speed sensor, laser interferometer, lubrication system, cooling system, chip removal system; Scheme S2: large cutter disk, main shaft box, gear blank clamper, gear pitch mechanism, X-direction NC slide, Y-direction NC slide, Z-direction NC slide, body, upright column, foundation, numerical control device, electrical control system, hydraulic system, speed sensor, cooling system, lubrication system; Scheme S3: large cutter disk, main shaft box, gear blank clamper, gear pitch mechanism, X-direction NC slide, Y-direction NC slide, body, upright column, foundation, numerical control device, electrical control system, pneumatic system, speed sensor, chip removal system, cooling system.

In order to verify the effectiveness and reliability of the evaluation method of machine tool module configuration design scheme based on triangular fuzzy number and set pair analysis theory, three groups of module configuration schemes are analyzed comprehensively considering five evaluation factors of reliability, production cost, manufacturing speed, extensibility and disassembly, and the optimal configuration design scheme is selected to meet the actual needs of production.

Through the analysis of three experts in the industry, the fuzzy linguistic values of three groups of schemes in five evaluation factors are obtained, as shown in Table 2.

Compared with Table 1, the fuzzy linguistic values in Table 2 are transformed into standardized triangular fuzzy numbers, which are transformed into fuzzy comprehensive evaluation values according to formula (6), and the evaluation decision matrix \( D = [d_{ij}^1, d_{ij}^2, d_{ij}^3] \) is constructed.

### Table 2. Fuzzy language value of evaluation factor.

| Configuration scheme | Expert evaluation | Evaluating factor | Reliability | Production costs | Manufacturing speed | Extensibility | Disassembly |
|----------------------|-------------------|-------------------|-------------|------------------|---------------------|--------------|------------|
| S1                   | P1                | Good              | Middle      | Very good        | Middle lower        | Middle upper | Middle upper |
|                      | P2                | Very good         | Middle upper| Good             | Good               | Good         | Very good   |
|                      | P3                | Good              | Middle upper| Middle upper     | Good               | Very good    | Good        |
| S2                   | P1                | Middle            | Very good   | Middle upper     | Middle lower        | Good         | Middle upper |
|                      | P2                | Middle upper      | Good        | Good             | Good               | Very good    | Middle upper |
|                      | P3                | Good              | Good        | Good             | Good               | Middle upper | Middle upper |
| S3                   | P1                | Middle lower      | Middle      | Very good        | Good               | Middle upper | Middle      |
|                      | P2                | Middle upper      | Very good   | Good             | Good               | Middle upper | Middle      |
|                      | P3                | Middle            | Good        | Very good        | Good               | Good         | Very good   |
Table 3. BNP values of 5 evaluation factors.

| Configuration scheme | Reliability | Production costs | Manufacturing speed | Extensibility | Disassembly |
|----------------------|-------------|------------------|---------------------|---------------|-------------|
| S1                   | 1.037       | 0.778            | 0.981               | 0.981         | 0.981       |
| S2                   | 0.834       | 1.037            | 0.834               | 0.815         | 0.778       |
| S3                   | 0.667       | 0.926            | 1.037               | 0.888         | 0.870       |

Table 4. BNP value standardization results of 5 evaluation factors.

| Configuration scheme | Reliability | Production costs | Manufacturing speed | Extensibility | Disassembly |
|----------------------|-------------|------------------|---------------------|---------------|-------------|
| S1                   | 0.402       | 0.724            | 1                   | 1             |             |
| S2                   | 0.451       | 1                | 0                   | 0             | 0           |
| S3                   | 0            | 0.464            | 1                   | 0.440         | 0.453       |

$$D = \begin{bmatrix} 0.722, 0.889, 1.000 & 0.444, 0.611, 0.778 & 0.667, 0.833, 0.944 & 0.667, 0.833, 0.944 & 0.667, 0.833, 0.944 \\ 0.500, 0.667, 0.833 & 0.722, 0.889, 1.000 & 0.500, 0.667, 0.833 & 0.500, 0.667, 0.778 & 0.444, 0.611, 0.778 \\ 0.333, 0.500, 0.667 & 0.611, 0.778, 0.889 & 0.722, 0.889, 1.000 & 0.556, 0.722, 0.889 & 0.556, 0.722, 0.833 \end{bmatrix}$$

According to formula (5), the best non-fuzzy performance value $BNP$ of fuzzy comprehensive evaluation value is calculated, as shown in Table 3.

According to formula (7), the normalized results of $BNP$ values are obtained, as shown in Table 4.

According to equation (8), the information entropy of five evaluation factors is calculated. They were 0.402, 0.568, 0.619, 0.560, and 0.565, respectively.

According to equations (9) and (10), the weights of five evaluation factors are calculated 0.262, 0.189, 0.167, 0.192, and 0.190, respectively.

$$\mu = \begin{bmatrix} 0.722 + 0.278i & 0.444 + 0.334i + 0.222j & 0.667 + 0.277i + 0.056j & 0.667 + 0.277i + 0.056j & 0.667 + 0.277i + 0.056j \\ 0.500 + 0.333i + 0.167j & 0.722 + 0.278i & 0.500 + 0.333i + 0.167j & 0.500 + 0.278i + 0.222j & 0.444 + 0.334i + 0.222j \\ 0.333 + 0.334i + 0.333j & 0.611 + 0.278i + 0.111j & 0.722 + 0.278i & 0.556 + 0.333i + 0.111j & 0.556 + 0.277i + 0.167j \end{bmatrix}$$

$$\mu' = \begin{bmatrix} 0.923 + 0.077i & 0.592 + 0.112i + 0.296j & 0.852 + 0.077i + 0.071j & 0.852 + 0.077i + 0.071j & 0.852 + 0.077i + 0.071j \\ 0.667 + 0.111i + 0.223j & 0.923 + 0.077i & 0.667 + 0.111i + 0.223j & 0.639 + 0.077i + 0.284j & 0.592 + 0.112i + 0.296j \\ 0.444 + 0.112i + 0.444j & 0.781 + 0.077i + 0.142j & 0.923 + 0.077i & 0.741 + 0.111i + 0.148j & 0.710 + 0.077i + 0.213j \end{bmatrix}$$

The set pair $H = (S_k, S_0)$ between configuration scheme $S_k$ and ideal optimal scheme $S_0$ is one-to-one correspondence with the set pair $H = (d_{ij}, 1)$ between evaluation value $[d_{ij}^1, d_{ij}^2, d_{ij}^3]$ and ideal value $[1, 1, 1]$. After obtaining the decision matrix $D$, the set pair between the evaluation value $[d_{ij}^1, d_{ij}^2, d_{ij}^3]$ and the ideal value $[1, 1, 1]$ is constructed, and the evaluation of the configuration scheme in the form of fuzzy number is transformed into the form of IDO connection coefficient

$$\mu_{ij} = a_{ij} + b_{ij} + c_{ij}$$

Where: $a_{ij}$ indicates the degree of reaching the ideal degree of the factor value $d_{ij}$, $a_{ij} = d_{ij}^1$, $b_{ij}$ indicates the degree of uncertainty of the factor value $d_{ij}$, $b_{ij} = d_{ij}^2 - d_{ij}^1$, $c_{ij}$ indicates the degree of not reaching the ideal degree of the factor value $d_{ij}$, thus, the decision matrix $\mu$ of scheme evaluation in the form of IDO coefficient can be obtained.

The improved scheme evaluation decision matrix $\mu'$ is obtained according to equation (11)

According to equation (12), the IDO expression of each improved scheme and the most ideal scheme is

$$\mu'_i = 0.821 + 0.084i + 0.095j$$
$$\mu'_2 = 0.696 + 0.098i + 0.206j$$
$$\mu'_3 = 0.695 + 0.093i + 0.212j$$
Calculate the closeness of each scheme according to equation (13)

\[ M(\mu'_1) = 0.896, M(\mu'_2) = 0.772, M(\mu'_3) = 0.766 \]

The priority value of closeness between each scheme and the ideal scheme is obtained by sorting, as follows:

\[ M(\mu'_1) > M(\mu'_2) > M(\mu'_3) \]

In order to more intuitively compare the advantages and disadvantages of each scheme, a histogram is drawn to express it, as shown in Figure 4.

It can be seen from Figure 4 that the production cost of scheme 1 is high and will be restricted in actual production. The factors of scheme 2 are relatively balanced and the production cost advantage is obvious. This scheme can be considered in mass orders. The reliability of scheme 3 is poor and all factors are not prominent. Enterprises can choose appropriate schemes according to the actual situation. The layout of the module configuration scheme for special machine tool of variable hyperbolic circle-arc-tooth-trace cylindrical gear is shown in Figure 5.

The composition, function, assembly and motion relationship of each module are as follows:

The main shaft box module is fixed on the leftmost side of the body, which is used to make the shaft drive the large cutter disk to rotate according to the specified speed, so as to realize the rotary movement of the cutter.

The body module is composed of a body and a foundation. The body is fixed on the base of the machine tool. It is used to support all parts of the machine tool. It is used to support all parts of the machine tool.

The gear blank clamper and gear pitch mechanism belong to the work piece fixing and pitch module, which are installed on the upright column and realize the horizontal feeding movement of the work piece through the sliding module.

The cooling module is composed of a cooling device and a cooling circulating pump, which is fixed on the body module to provide sufficient cutting fluid for the machine tool in processing and meet the requirements of cutting processing.

During cutting, on the one hand, the gear blank to be machined rotates at a speed \( \omega_1 \) around its own axis, on the other hand, make a horizontal movement close to the large cutter disk along the horizontal direction, and the speed is \( V_1 \) forming a close generative movement with the cutter. During the machining process, the cutter cuts out the concave convex tooth surface of the gear at the identity time. After machining a pair of tooth surfaces, it is necessary to pitch them and then process the next pair of tooth surfaces until the machining of the whole gear is completed. Here,

\[ V_1 = \omega_1 \times R_1 \]  \hspace{1cm} (15)

\( R_1 \) is the gear pitch radius.
Conclusions

Based on the module division of the special machine tool for variable hyperbolic circular-arc-tooth-trace cylindrical gear, the module retrieval is completed through the calculation of the similarity coefficient of the quantitative attribute of the module, the design process of the module configuration scheme is proposed, and the evaluation and optimization of three module configuration design schemes are completed. The feasibility and effectiveness of the method proposed in this paper are verified, and the following conclusions are drawn:

1. Through the module retrieval strategy, the purpose of retrieving the nearest module instance is achieved.
2. This paper presents a new idea to eliminate the subjectivity of different experts’ judgment by evaluating the language value of evaluation factor based on triangular fuzzy number and calculating the weight combined with entropy weight method.
3. The set pair analysis theory is used to analyze the fuzziness of the evaluation factor of the module configuration scheme of the machine tool, the identity, different and opposite connection degree of the module configuration scheme is improved, and the mathematical evaluation model of the identity, different and opposite module configuration scheme of the machine tool is established.
4. The scheme closeness is introduced to sort the machine tool module configuration schemes, draw a histogram to analyze the evaluation factors of each scheme, and obtain the machine tool module configuration design scheme that meets the requirements.
5. This method is also applicable to the multi scheme evaluation of any complex mechanical and electrical products, and provides a new and more objective calculation idea for multi-objective decision-making.

Because each factor in the evaluation of machine tool module configuration design scheme is not independent, there are mutual connections and constraints between them. Improving and perfecting the evaluation model and method of machine tool module configuration design scheme is the focus of the next research.

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