Structure optimization design of transmission system of shearer cutter based on genetic algorithm

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Abstract. As one of the mainstream equipment of fully mechanized mining equipment, shearer is a large complex system with the functions of breaking coal and transporting coal. It is an important milestone for China's coal industry to move towards modernization and mechanization. In order to adapt to the complex working environment and better meet the needs of social development, the optimization of spatial structure and bearing capacity of coal machine has become the focus of research. Based on genetic algorithm, taking MG500/1170-AWD1 electric haulage shearer as an example, this paper takes the weight function of maximizing the bearing capacity and minimizing the volume as the optimization objective to optimize the structure of the cutting part transmission system, and analyses the rationality of the scheme by comparing the objective function before and after optimization, so as to provide technical support for the R & D department.

Keywords: Shearer; optimal bearing capacity; minimum volume; structure optimization; genetic algorithm

1. Introduction
As an important natural resource of national strategic development, coal has a positive impact on promoting social and economic development. In order to meet the needs of energy supply and serve the society, the improvement of coal mining is still an urgent problem to be solved. Based on the existing tools, optimizing the design of more efficient and energy-saving mining equipment has become the core step of the research. As one of the mainstream equipment of fully mechanized mining equipment, shearer is a large complex system with the functions of breaking coal and transporting coal. It is an important milestone for China's coal industry to move towards modernization and mechanization. In order to adapt to the complex working environment and better meet the needs of social development, the optimization of spatial structure and bearing capacity of coal machine has become the focus of research.

At present, the structure optimization of transmission system of cutter mainly takes the minimum volume as the optimization objective, and does not consider the impact of the optimal bearing capacity on the performance improvement of the equipment. In order to solve the above problems, this paper takes MG500/1170-AWD1 electric haulage shearer as an example based on genetic algorithm, takes the weight function of maximum carrying capacity and minimum volume as the optimization objective, optimizes the structure of the cutting part transmission system, and analyzes the rationality of the...
scheme by comparing the objective function before and after optimization, so as to provide technical support for the R & D department.

2. Establishment of optimization model of cylindrical gear double stage planetary reducer system

MG500/1170-AWD1 electric haulage shearer is a kind of electric haulage shearer with multi motor drive, motor transverse arrangement and airborne AC frequency conversion speed regulation device. The total installed power of this machine is 1170kW, and the single rocker cutting motor is 500kW. It is suitable for the coal seam with the thickness of 1.6~3.4m, the working face inclination angle of less than 35° and the coal hardness of \( f \leq 4 \). It can be self-operated and bi-directional coal mining. It is equipped with heavy rock breaking drum and can cut the coal seam with a certain thickness of gangue.

As shown in Fig.1 is the schematic diagram of the transmission system of the shearer cutting part. The motor torque is transmitted by four stages, including two-stage involute and two-stage planetary mechanism. The speed adjustment is realized through the reduction of spur gear and planetary gear.

![Fig. 1 Schematic diagram of shearer cutting part transmission system](image)

In Fig.1, \( Z_1 \) is a one axis component gear, \( Z_2 \) is a two axis component idler, \( Z_3 \) is a three axis component pinion, \( Z_4 \) is a three axis big gear, \( Z_5 \) is a four axis component idler, \( Z_6 \) is a seven axis component gear, \( Z_{a1}, Z_{b1}, Z_{c1} \), and \( Z_{a2}, Z_{b2}, Z_{c2} \) are the sun gear, ring gear and asteroid gear in the first and second stage planetary gear trains respectively.

2.1. Establishment of mathematical model of objective function

At present, the goal of reducer optimization is mainly divided into three categories: maximum bearing capacity, minimum volume and maximum economic benefit. Considering the working characteristics of shearer and the requirements of environmental factors, this paper takes the weight function of maximizing the bearing capacity and minimizing the volume as the optimization objective function, and the weight coefficients are 0.702 and 0.298 respectively. At this time, the bearing capacity and structural compactness reach the best dynamic degree, which can better adapt to the complex construction environment.

The main factors affecting the load-bearing capacity of "involute cylindrical gear-two-stage planetary mechanism" reduction system include the contact stress \( \sigma_{H1}, \sigma_{H2}, \sigma_{H3} \) of the tooth surface of the first-stage involute transmission gear pair and the bending stress \( \sigma_{F1}, \sigma_{F2}, \sigma_{F3} \) at root. The second-stage involute transmission gear pair tooth surface contact stress \( \sigma_{H4}, \sigma_{H5}, \sigma_{H6}, \sigma_{H7}, \sigma_{H8} \) and tooth root bending stress \( \sigma_{F4}, \sigma_{F5}, \sigma_{F6}, \sigma_{F7}, \sigma_{F8} \), the first-stage planetary gear tooth surface comprehensive contact stress \( \sigma_{H9} \) and tooth The root bending stress \( \sigma_{F9} \), the comprehensive contact stress \( \sigma_{H10} \) of the tooth surface of the second-stage planetary mechanism and the comprehensive bending stress \( \sigma_{F10} \) of the tooth root, so the mathematical model of the load-bearing capacity \( \sigma \) of the transmission system:

\[
\sigma = \left\{ \sigma_{Hi}, \sigma_{Fi} \right\}
\]
Where:

\[ \sigma_{sh} = \{ \sigma_{h1}, \sigma_{h2}, \sigma_{h3}, \sigma_{h4}, \sigma_{h5}, \sigma_{h6}, \sigma_{h7}, \sigma_{h8}, \sigma_{h9}, \sigma_{h10} \} \]

\[ \sigma_{fs} = \{ \sigma_{f1}, \sigma_{f2}, \sigma_{f3}, \sigma_{f4}, \sigma_{f5}, \sigma_{f6}, \sigma_{f7}, \sigma_{f8}, \sigma_{f9}, \sigma_{f10} \} \]

The main influencing factors affecting the volume of the reduction system of "involute cylindrical gear-two-stage planetary mechanism" are the volume of the one-axis assembly gear \( V_1 \), the volume of the two-axis assembly idler \( V_2 \), the volume of the three-axis assembly pinion \( V_3 \), and the volume of three-axis large gear \( V_4 \), Four-axis component idler volume \( V_5 \), \( V_6 \) and \( V_7 \), where \( V_5 = V_6 = V_7 \), seven-axis component gear volume \( V_8 \), two-stage planetary mechanism sun gear volume \( V_{a1} \) and \( V_{a2} \), ring gear volume \( V_{b1} \) and \( V_{b2} \), small planetary gear volume \( V_{c1} \) and \( V_{c2} \), Therefore, the mathematical model of the total volume \( V_s \) of the transmission system is:

\[
V_s = V_1 + V_2 + V_3 + V_4 + V_5 + V_6 + V_7 + V_8 + V_{a1} + V_{a2} + V_{b1} + V_{b2} + V_{c1} + V_{c2}
\]

\[
\approx \pi \left( \frac{m_1 \tau_{z1}}{4} b_1 + \frac{m_2 \tau_{z2}}{4} b_2 \right) + \pi \left( \frac{m_3 \tau_{z3}}{4} b_3 + \frac{m_4 \tau_{z4}}{4} b_4 \right) + \pi \left( \frac{m_5 \tau_{z5}}{4} b_5 \right)
\]

\[
(2)
\]

Where: \( m_1, m_2 \) are the modulus of the two-stage involute transmission gear pair respectively, \( b_1, b_2 \) are the tooth width of the two-stage transmission gear pair, \( \tau_{z1} \sim \tau_{z6} \) are the number of teeth of the gears of the one-shaft assembly to the seven-axis assembly respectively, \( m_3, m_4 \) are the modulus of the two-stage planetary gears respectively, \( b_3, b_4 \) is the tooth width of the two-stage planetary gear, \( \tau_{z1} \sim \tau_{z6} \) and \( \tau_{z7} \sim \tau_{z12} \), \( \tau_{z12} \) are the number of teeth of the sun gear, ring gear and pinion gear in the first and second stage planetary mechanisms respectively.

After weighting the two types of optimization functions, the final objective function is obtained, and its mathematical expression is:

\[
F(s) = 0.702 \sigma_s + 0.298 V_s
\]

(3)

2.2. Design variables

Variables that have a greater impact on the final optimization function include: the number of teeth, modulus, and tooth width of each gear train. Therefore, the design variables are determined as:

\[
X = [x_1, x_2, x_3, \ldots, x_{20}]^T
\]

\[
= [m_1, m_2, b_1, b_2, \tau_{z1}, \tau_{z2}, \tau_{z3}, \tau_{z4}, \tau_{z5}, \tau_{z6}, m_3, m_4, b_3, b_4, \tau_{z7}, \tau_{z8}, \tau_{z9}, \tau_{z10}, \tau_{z11}, \tau_{z12}]
\]

(4)

3. Optimization of the cutting part system of the shearer

3.1. Constrained optimization conditions

Because there are many gear trains in the shearer transmission system, the constraint conditions are relatively complex, including gear contact and bending strength inspection indexes, the relative installation positions of the gear trains, and the influence of the boundary conditions of the basic parameters of the gears on the objective function. The optimization constraint conditions of cylindrical gears and planetary mechanisms will be studied as follows.
3.1.1. Involute gear strength constraint index. From the perspective of the operational reliability of the gear pair and the safety of the mechanical equipment, the tooth strength needs to be checked. The specific manifestation is that the tooth surface contact stress and tooth root bending stress obtained through theoretical solutions should be less than the corresponding allowable value, which is:

\[
\begin{cases}
\sigma_{Ht} \leq \sigma_{Ht}^\text{le} \\
\sigma_{Fr} \leq \sigma_{Fr}^\text{le}
\end{cases}
\]  
(5)

3.1.2. Tooth number constraint. In order to avoid the occurrence of undercutting, the design number of teeth of a standard involute gear with a pressure angle of 20° should not be less than 17. However, in the transmission of planetary mechanism, the number of teeth of the sun gear shall not be less than 16. Assuming that the transmission ratio remains unchanged, when the number of teeth of the driving wheel increases, the overall volume of the transmission pair increases. When the center distance is constant, increasing the number of driving gear teeth can increase the coincidence degree and improve the transmission stability, but at the same time the modulus decreases, the thickness of the gear teeth decreases, and the overall strength is reduced. Therefore, the number of driving gear teeth \( z_1 \) should meet:

\[ z_{\text{min}} \leq z_1 \leq z_{\text{max}} \]  
(6)

In the formula, \( z_{\text{min}} \) is the minimum number of teeth of the gear, and \( z_{\text{max}} \) is the maximum number of teeth of the gear.

3.1.3. Modulus constraints. Since the gear train needs to transmit power and torque, in order to prevent the gear teeth from breaking due to insufficient strength, the modulus is required to be not too small, generally greater than or equal to 2, but too large modulus will increase the volume of the gear, so the modulus \( m \) should meet:

\[ m_{\text{min}} \leq m \leq m_{\text{max}} \]  
(7)

In the formula, \( m_{\text{min}} \) is the minimum module of gear, and \( m_{\text{max}} \) is the maximum module of gear.

3.1.4. Coincidence constraint. In order to continuously drive the gear pair, it is necessary to ensure that when the front pair of teeth is not disengaged from the mesh, the rear pair of teeth participates in the mesh in time. Therefore, the coincidence degree \( \varepsilon \) should satisfy:

\[ \varepsilon \geq \varepsilon_{\text{min}} \]  
(8)

In the formula, \( \varepsilon_{\text{min}} \) is the minimum coincidence degree that meets the continuous transmission of the gear pair.

3.1.5. Tooth width factor. The choice of tooth width parameters has a direct effect on the strength of the gear teeth. The larger the tooth width, the stronger the load-carrying capacity of the gear, but it will reduce the uniformity of the tooth surface load distribution and increase the eccentric load effect. Therefore, the tooth width coefficient \( \varphi_{d} \) should satisfy:

\[ \varphi_{d_{\text{min}}} \leq \varphi_{d} \leq \varphi_{d_{\text{max}}} \]  
(9)
Where, $\varphi_{d,\text{min}}$ is the minimum value of tooth width coefficient, $\varphi_{d,\text{max}}$ is the maximum value of tooth width coefficient.

### 3.1.6. Center distance requirements

The design center distance of the spur gear drive should be limited between the maximum and minimum center distances that meet the design requirements:

\[
a_{\text{min}} \leq \sum_{i=1}^{N} a_i \leq a_{\text{max}}
\]  

In the formula, $a_{\text{min}}$ is the minimum center distance that meets the design requirements, $a_{\text{max}}$ is the maximum center distance that meets the design, and $N$ is the number of transmission stages.

### 3.1.7. The constraint conditions of two-stage planetary mechanism transmission

In order to meet the conditions of correct meshing of planetary gears, the strength inspection index, and the relative installation position of the planetary gears, the concentricity requirements and the variation boundaries of various variables should be taken into consideration when restraining.

1. **Strength inspection index**

   In order to meet the requirements of meshing transmission, referring to the strength calculation theory of external meshing cylindrical gear, the strength constraint index of planetary gear is deduced: the two-stage sun gear $z_1$ and $z_2$ should meet the tooth surface contact fatigue strength and tooth root bending fatigue strength, and all levels of planetary gear should also meet the strength requirements.

2. **Installation conditions**

   In order to meet the assembly process requirements of the planetary gear and ensure the smooth installation of each component, it is necessary to ensure that there is a reasonable functional correspondence between the planetary gear and the sun gear.

3. **Concentricity requirements**

   The trajectories of the central axes of the planetary gears should be coincident, that is to say, the distance between the central axis of the sun gear and the central axis of the planetary gears must be equal, that is, the concentric constraint. The mathematical expression is:

\[
l_{a1} + 2l_{a1} = l_{b1}
l_{a2} + 2l_{a2} = l_{b2}
\]  

4. **The change boundary of each variable**

   Each design variable has a margin range, and value should be in a reasonable range in the design.

### 3.2. Optimization algorithm design

There are many design variables in the optimization objective function of shearer cutting part drive system, and the constraints are relatively complicated, which makes the solution more difficult. In order to find out the optimal design parameters, it is necessary to find out a reasonable optimization algorithm. In this paper, genetic algorithm is selected as the basis for solving, which has guiding significance for getting a more perfect optimization scheme.

#### 3.2.1. Genetic algorithm

Based on Darwin's biological genetic theory, genetic algorithm inherits the phenomena of selection, crossover and mutation in nature, and integrates the operation principle of random statistics. Basic principle: first, a group of population is preliminarily selected, and a group of individuals that are more suitable for the natural environment are generated through the selection, crossover and mutation process. Then, the exploration area is optimized. After iterative optimization, a group of individual parameters that are most suitable for the objective function are obtained.
3.2.2. Establishment of mathematical model for optimal solution of transmission system. According to the basic implementation steps of genetic algorithm, when the weight of optimal carrying capacity and minimum volume is taken as the objective function, the following parameters need to be designed: coding, constraint optimization boundary, algorithm determination.

(1) Coding

Coding is the premise of genetic algorithm. The design variable is taken as the research object, which is compiled into the corresponding chromosome by a certain algorithm, and its gene represents the specific value. In this paper, through the binary coding technology, the design variables are converted to the binary code recognized by the computer for corresponding reading and storage. Involute cylindrical gear- two-stage planetary transmission system has 20 design variables, so 20 chromosome units composed of binary code are proposed.

(2) Constrained optimization boundary

Because the genetic algorithm cannot solve the constraint function, the penalty function can be used to solve this kind of constraint problem. The design idea of the penalty function is to combine the objective function and the constraint function to form a new objective function:

\[
\begin{aligned}
\min & \quad f(x) \\
\text{s.t.} & \quad h_i(x) = 0, i = 1, 2, 3 \ldots, I \\
& \quad g_j(x) \leq 0, j = 1, 2, 3 \ldots, M
\end{aligned}
\]  
(12)

Change the above formula into:

\[
\begin{aligned}
\min (F(x, \sigma)) & = f(x) + \sigma P(x) \\
F(x, \sigma) & = F(x)
\end{aligned}
\]  
(13)

Where: \(\sigma\) is the value tending to infinity, \(P(x)\) is the determined continuous function:

\[
P(x) = \sum_{i=0}^{j} \lambda_i h_i(x) + \sum_{j=0}^{M} \mu_j g_j(x)
\]  
(14)

For the determination of the weighting coefficient, there are the following conditions:

\[
\begin{aligned}
\lambda(y) & = 0, y = 0 \\
\mu(y) & = 0, y = 0 \\
\lambda(y) & > 0, y \neq 0 \\
\mu(y) & > 0, y \neq 0
\end{aligned}
\]

(3) Determination of algorithm

4. Select

The selection algorithm is to select the individuals with high fitness in the population and pass them on to the next generation. The probability of the individuals with high fitness passing on to the next generation is relatively large, so Roulette is used as the design basis of the selection algorithm. That is to say, the probability that an individual inherits the next generation is the ratio of the fitness of the individual to the sum of the fitness of all populations, and its mathematical expression is:

\[
p_i = \frac{q(x)}{\sum_{i=1}^{N} q(x)}
\]  
(15)
5. Crossover
In this paper, single crossover is used as the research basis, that is, two individuals can be selected and chromosome parameters can be exchanged through any crossover point.

6. Variation
Mutation is a phenomenon that the next group of population individuals is generated by gene mutation with a certain small probability in nature. The number of mutation individuals in the process of solving is determined by the mutation probability \( P_m \). The advantage of mutation is to ensure the diversity of the population and prevent the dilemma of entering the local optimal solution.

7. Optimization scheme of transmission system
The comparison of objective functions before and after optimization is shown in Table 1, and the objective functions before and after optimization is reduced to some extent. In the spur gear transmission system, the design parameters of the primary straight tooth transmission system vary greatly, among which the target function of the three-axis gear assembly is reduced by the largest amount, the function ratio before and after optimization is about 91.3%. The modulus of the secondary straight tooth transmission system does not change before optimization. Only a small change is made in the number of teeth and tooth width, and the target function ratio is about 98%. In planetary transmission system, the modulus is not changed, but the tooth width is lower than before optimization, and the target function ratio is floating between 93% and 97%, and optimization effect is significant.

| NO. | Before optimization | After optimization | CMPR |
|-----|---------------------|--------------------|------|
|    | \( z \) | \( m \) | \( b \) | \( F(x) \) | \( z \) | \( m \) | \( b \) | \( F(x) \) |       |
| \( Z_1 \) | 26 | 8 | 105 | 597.5 | 25 | 9 | 102 | 555.0 | 92.9% |
| \( Z_2 \) | 39 | 8 | 105 | 597.2 | 39 | 9 | 102 | 556.7 | 93.2% |
| \( Z_3 \) | 35 | 8 | 105 | 479.2 | 34 | 9 | 102 | 437.6 | 91.3% |
| \( Z_4 \) | 30 | 9 | 105 | 470.9 | 31 | 9 | 102 | 464.8 | 98.7% |
| \( Z_5 \) | 38 | 9 | 105 | 471.9 | 38 | 9 | 102 | 466.0 | 98.7% |
| \( Z_6 \) | 47 | 9 | 105 | 375.7 | 49 | 9 | 102 | 375.2 | 99.8% |
| \( Z_{a1} \) | 25 | 7 | 90 | 330.5 | 24 | 7 | 80 | 323.9 | 98.0% |
| \( Z_{b1} \) | 25 | 7 | 85 | 289.2 | 25 | 7 | 75 | 280.1 | 96.9% |
| \( Z_{c1} \) | 77 | 9 | 70 | 244.6 | 75 | 7 | 80 | 240.5 | 93.0% |
| \( Z_{a2} \) | 23 | 9 | 135 | 230.7 | 21 | 9 | 125 | 220.4 | 95.5% |
| \( Z_{b2} \) | 24 | 9 | 120 | 212.5 | 27 | 9 | 115 | 206.8 | 97.3% |
| \( Z_{c2} \) | 75 | 9 | 130 | 197.7 | 75 | 9 | 120 | 193.3 | 97.8% |

8. Conclusion
At present, the improvement of coal resources mining capacity is still an urgent problem. It is the core step of the research to optimize the design of mining equipment with more efficient and energy saving based on existing tools. In order to adapt to complex working environment and meet the needs of social development, the optimization of spatial structure and bearing capacity of Shearer has become the focus of the research. Based on genetic algorithm, taking MG500 / 1170-awd1 electric traction shearer as an example, the weight function of maximum bearing capacity and volume minimization is taken as the optimization objective to optimize the structure of the cutting part transmission system. Through the analysis of the objective function before and after optimization, it can be seen that the bearing capacity of shearer is greatly improved after the optimization, and the space volume has a certain range to reduced, which is more in line with the complex working conditions.
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