Dynamic Optimization Design of Transverse Axis Cutting Reducer

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Abstract. Focused on the gear transmission system of a certain type of transverse axis cutting reducer, this paper firstly establishes the ADAMS virtual prototype model for calculating the dynamic load coefficient of the system, and the influence of gear modulus and tooth width factor on the dynamic load coefficient of the system is determined by multiple linear regression. Then the GA-BP neural network model for calculating the dynamic load coefficient of the system is constructed based on Genetic Algorithm (GA) and BP neural network, which makes the decoupling of the system dynamics analysis and optimization design process be realized. Finally, based on the above analysis, a multi-objective optimization design with the goal of minimizing the system volume and dynamic load coefficient is carried out. The calculation results show that the gear transmission system of the transverse axis cutting reducer is optimized efficiently, and its volume is reduced by 18.8%, and the dynamic load coefficient is decreased by 11.5%. This paper starts with the system dynamics analysis, makes the GA-BP neural network model as the bridge, and finally establishes the technical method for dynamic analysis optimum design of the transverse axis cutting reducer. The analytical technique and method can provide reference for the optimization design analysis of complex gear transmission system.

1. Introduction

Boom-type roadheader is the main machinery for tunneling in coal mine roadway. According to its cutting head arrangement, it can be divided into longitudinal axis type and transverse axis type. Compared with the longitudinal axis type, the unstable moment produced by the transverse axis roadheader when cutting coal is opposite to the stable moment formed by the machine gravity, which has the advantages of enhancing the cutting efficiency and stability. Thus, the development of transverse axis roadheader with high performance and high power has become the mainstream direction of today's mining industry[1].

In the boom-type roadheader, the cutting reducer is the most important power transmission factor, its working performance determines the actual capacity and efficiency of the roadheader[2], the design and manufacture of high power and high reliability cutting reducer is one of the important research topics in this field. Jiao Xinxin et al. verified the transmission ratio of EBZ-135 boom-type roadheader cutting reducer based on virtual prototype technology, and carried out quality optimization and fatigue
life analysis of some key parts[3]. Yin min et al. studied the vibration of a cutting reducer by analysis, they found that the noise of cutting reducer is mainly caused by the dynamic meshing force of gears, and adding staggered stiffener can reduce the vibration[4]. LV Xiaodan et al. completed the structural optimization design of cutting reducer with the goal of simplifying structure, reducing volume and gear module[5]. Wu Shiwen et al. took the minimum volume as the objective, and used MATLAB optimization toolbox to optimize the volume of cutting reducer[6]. Zhang Qiang et al. used the multi-objective fuzzy reliability optimization strategy of genetic algorithm to optimize the motion parameters of the cutting head, and it worked[7]. Wang Fuqiang et al. tested the function parameters of the EBH-315 road-header and provided a data reference for its performance study[8]. Zhu Shengqi et al. improved the production process of the planetary carrier of the longitudinal cutting reducer to enhance its production efficiency and performance[9].

It can be found that the researches on the design and analysis of the cutting reducer are mainly focused on the longitudinal axis type, but less on the transverse axis type with more complex structure. Moreover, as a power transmission device mainly composed of gear transmission, under the action of internal and external excitations such as cutting resistance and dynamic tooth meshing force, the cutting reducer generates strong vibration and noise inevitably[10,11]. Therefore, the dynamic analysis and optimization design of the gear system of cutting reducer based on the dynamic analysis have great significance for improving the working performance of the cutting reducer and the reliability of the whole roadheader. However, the dynamic analysis of the gear system is carried out with solving the nonlinear equations or virtual simulation generally, it makes the coupling of nonlinear equations solution or virtual simulation and optimization when considering the dynamic performance on optimization process. This is also the reason that hinders the relevant optimization work.

Therefore, this paper integrates ADAMS virtual prototype, multiple linear regression, BP neural network, Genetic Algorithm (GA), multi-objective optimization design and other theories and techniques to develop characteristic analysis and optimization design of the gear transmission system for the transverse axis cutting reducer. Its starting from system dynamics analysis, using GA-BP neural network as a bridge and finally optimizing the system structure, which provides a reference for the optimization design analysis of complex gear transmission system.

2. Optimization design variable decision based on dynamics simulation and multiple linear regression

For the optimization design problem, the selection of optimized design variables has a direct impact on its efficiency and effect. In order to determine the design variables for the dynamic performance optimization of the transverse axis cutting reducer gear transmission system. Firstly, based on ADAMS, the system dynamics simulation model is established, and the dynamic load of the system in work process is calculated. Then, the multivariate linear regression is applied to analyse the influence degree of each gear structural parameter on the dynamic performance of the gear system. At the same time, the optimized design variables are determined.

In this paper, the gear transmission system of a transverse axis cutting reducer produced by Yankuang Group is taken as the research object which is shown in Figure 1. Its input power is 20kW, the input speed is 1470rpm, and the output speed is 21rpm.

The virtual prototype model of the gear transmission system is established in ADAMS. In order to improve the simulation efficiency, the model is simplified as follows:
- The planetary gears on the left and right sides are symmetrical, so only one side is retained;
- Ignore the parts such as gaskets, retaining rings, keyways, chamfers, etc.
- The supporting effect of bearings are simplified as spring-damper elements operating at the journal.

And, the impact model is applied to define the impact contact force of each gear pair in the system, and its function expression is as follows:

$$F_c = \text{MAX}(0, K(q_0 - l)^r - C \times (dl/dt) \times \text{STEP}(l, q_0 - d, 1, q_0, 0))$$

(1)

Where $K$ is the contact stiffness coefficient; $q_0$ is the initial distance between two contact objects;
is the actual distance between the two contact objects; $\epsilon$ is the rigid force index; $C$ is the damping rate; $dl/dt$ is the relative speed between the two objects; $d$ is the penetration depth when the damping rate reaches the maximum. In this paper, the contact of gear meshing pair is the metal-metal contact, thus, the rigid force index is set to 1.5, the damping ratio is 0.01%, and the penetration depth is 0.1 mm. In addition, the Coulomb friction model is applied to express the friction between the gear pairs, the dynamic friction coefficient is 0.08, and the static friction coefficient is 0.1.

After the above processing and setting, the virtual prototype model is shown in Figure 2.

**Figure 1.** Structure of transverse axis cutting reducer  
**Figure 2.** Cutting reducer gear transmission system virtual prototype model

Based on the above virtual prototype model, the dynamic simulation analysis is carried out, and the dynamic meshing force, also called dynamic load, of each gear pair in the working process are obtained, which is an important symbol to evaluate its dynamic characteristics[12]. Thus, in this paper, the dynamic load is made as one of the objectives of the following dynamic performance optimization of the cutting reducer. The dynamic load is expressed with the dynamic load coefficient in this paper, and the expression for the dynamic load coefficient is:

$$K_D = G / G_D$$

(2)

Where $G$ is the dynamic load of the gear pair obtained by simulation; $G_D$ is the nominal load of the gear pair calculated based on the relevant gear transmission design theory.

In order to further simplify the subsequent analysis and the optimization design process, the integrated maximum dynamic load coefficient of the system (the average of the maximum dynamic load coefficients of gear pairs in the system) is used to characterize the comprehensive dynamic performance of the system. Its expression is:

$$K_{D}^{\text{max}} = \left( K_{D_1}^{\text{max}} + K_{D_2}^{\text{max}} + K_{D_3}^{\text{max}} + K_{D_4}^{\text{max}} + K_{D_5}^{\text{max}} + K_{D_6}^{\text{max}} \right) / 6$$

(3)

Where $K_{D}^{\text{max}}$ is the comprehensive maximum dynamic load coefficient of the system; I, II, III and IV represent the first, second, third and fourth gear stage; $K_{D_1}^{\text{max}}$, $K_{D_2}^{\text{max}}$, $K_{D_3}^{\text{max}}$, $K_{D_4}^{\text{max}}$, $K_{D_5}^{\text{max}}$, $K_{D_6}^{\text{max}}$ are the maximum dynamic load coefficient of the first, second gear stage; $K_{D_{11}}^{\text{max}}$, $K_{D_{12}}^{\text{max}}$, $K_{D_{13}}^{\text{max}}$, $K_{D_{14}}^{\text{max}}$ are the maximum dynamic load coefficient of the third and fourth planetary gear transmission in external meshing; $K_{D_{21}}^{\text{max}}$, $K_{D_{22}}^{\text{max}}$, $K_{D_{23}}^{\text{max}}$, $K_{D_{24}}^{\text{max}}$ are the maximum dynamic load coefficient of the third and fourth planetary gear transmission in internal meshing.

Related researches illustrate that the influence of gear modulus on the dynamic performance of the gear transmission system is significant[13,14], so this paper determines the gear modulus of each stage $m_i$ ($i=I, II, III, IV$) as one of the optimized design variables. Furthermore, the sensitivity analysis between some other structural parameters (containing the tooth width factor $\Phi$, the pressure angle $\alpha$ and the helix angle $\beta_1$ of the first helical gear stage) and the dynamic performance (the integrated maximum dynamic load coefficient) of the gear system is carried out to determine the rest optimization design variable with the multiple linear regression, which is a statistical analysis method that uses the regression analysis in mathematical statistics to determine the quantitative relationship between multiple variables[15]. Its mathematical model is:

$$y = \lambda_0 + \lambda_1 x_1 + \lambda_2 x_2 + \lambda_3 x_3$$

(4)

Where the $y$ is the object variable, which is corresponding to comprehensive maximum dynamic
load coefficient in this paper; and the design variables are \( x_1 \), \( x_2 \) and \( x_3 \), which are corresponding to \( \Phi \), \( \alpha \), and \( \beta \) respectively; \( \lambda_1 \sim \lambda_3 \) are the regression coefficients.

To obtain the samples used in the multiple linear regression analysis, in a certain value range of tooth width factor, pressure angle and helix angle of the first helical gear stage (where \( \Phi \) takes 0.7~1.1, \( \alpha \) takes 14.5°~22.5°, \( \beta \) takes 9.064°~11.564°), The orthogonal experimental design method is used to plan the combination of the three parameters reasonably, and the system comprehensive maximum dynamic load coefficients under these parameter combinations are calculated based on the dynamics simulation model constructed above.

Through the multiple linear regression analysis of the samples, equation is obtained as follows:

\[
y = 5.0915 + 7.06x_1 - 0.228x_2 - 0.4140x_3
\]

(5)

The correlation coefficient of the regression equation is \( R=0.9998 \), which indicates that the regression effect of the equation is significant. And the regression coefficient of the tooth width factor is much larger than the latter two. Therefore, in this paper, the final optimized design variables are the gear drive modulus of each stage \( m_i \) (\( i=I, II, III, IV \)) and the tooth width factor \( \Phi \).

3. GA-BP neural network for calculating dynamic performance

The gear transmission system of transverse axis cutting reducer is complicated, and its dynamic simulation takes a long time. If make the system dynamics simulation embed in the optimization design process directly, the computational efficiency will be greatly reduced. That’s why the dynamic performance is ignored or simplified in the optimization design of the complex gear systems. Therefore, based on the genetic algorithm and BP neural network technology, this paper constructs the GA-BP neural network to calculate the dynamic performance (the integrated maximum dynamic load coefficient) of the gear system. The GA-BP neural network can provide the integrated maximum dynamic load coefficient under different structural parameters for the optimization design accurately and instantaneously, which relieves the coupling between dynamic simulation and optimization design.

BP neural network is widely used in the nonlinear fitting and pattern recognition. But it has the disadvantages of slow convergence and easy to fall into local minimum. So, this paper introduces Genetic Algorithm to optimize the weights and thresholds of BP neural network, which makes the BP neural network trains operate near the global minimum, then increases its convergence speed and avoids from falling into local minimum.

Similar to the multivariate linear regression, the GA-BP neural network also needs some samples. Thus, the orthogonal experimental design method and dynamic simulation models established in this paper are also used to obtain the samples (while the value ranges of the parameters are as following: \( m_i \) is from 7 to 16, \( m_{\mu} \) is from 20 to 28, \( m_{\nu} \) is from 7 to 16, \( m_{\nu} \) is from 10 to 18, and \( \Phi \) is from 0.7 to 1.1). Then, with these simples, an eligible GA-BP neural network for calculation of dynamic performance is obtained.

Figure 3 shows the comparison between the results of the verification samples calculated with the simulation models and the GA-BP neural network. It can be seen that the relative error between the two results is not more than 2%, which indicates that the GA-BP neural network for calculating the dynamic performance of the gear system has great generalization ability, it can provide the integrated maximum dynamic load coefficient under different structural parameters for the optimization design accurately and instantaneously.

Figure 3. Verification sample error
4. Structural parameter optimization design

In view of the above work, with the multiple objectives of decrease the volume and dynamic load for the gear system of transverse axis cutting reducer, a multi-objective optimization design model is established in this paper based on the linear weighted sum method.

With the linear weighted sum method, the design variables are written as the followed vector form:

\[ x = [x(1), x(2), x(3), x(4), x(5)]^T = [m_1, m_2, m_3, m_4, \Phi]^T \]  \hspace{1cm}  (6)

And the total volume of the gear system can be expressed as V:

\[ V = \frac{28\pi(x(2) \times 28)^2 \times x(2) \times 5 + 79\pi(x(3) \times 79)^2 \times x(3) \times 5 + 58\pi(x(4) \times 58)^2 \times x(4) \times 5)}{4} \]  \hspace{1cm}  (7)

According to the established GA-BP neural network, the integrated maximum dynamic load coefficient of the gear system can be written as follows:

\[ K_{max}^{int} = \text{postmnm}(\text{sim}(\text{net}_p, \text{tramnm}(x, \text{min}, \text{max})), \text{min}, \text{max}) \]  \hspace{1cm}  (8)

Based on the linear weighted sum method, the objective function is written as follows:

\[ F = \omega_1 V + \omega_2 K_{max} \]  \hspace{1cm}  (9)

Where \( \omega_1 \) is the weight of the objective variable of the total volume; \( \omega_2 \) is the weight of the objective variables of the integrated maximum dynamic load coefficient. In this paper, take \( \omega_1 = 0.4 \) and \( \omega_2 = 0.6 \).

In this paper, the constraints of optimal design are as follows:

\[ \begin{align*}
7 &\leq m_1 \leq 16 \\
20 &\leq m_2 \leq 28 \\
7 &\leq m_3 \leq 16 \\
10 &\leq m_4 \leq 18 \\
0.7 &\leq \Phi \leq 1.1
\end{align*} \]  \hspace{1cm}  (10)

Where \( K \) is the load coefficient; \( T \) is the torque; \( Y_{fa} \) is the tooth shape coefficient; \( Y_{sa} \) is the stress coefficient when the load acts on the tooth top; \( \sigma_f \) is the allowable bending fatigue strength of the tooth root; \( Z_e \) is the elastic influence coefficient; \( Z_H \) is the area coefficient; \( i \) is the transmission ratio; \( \sigma_H \) is the allowable contact fatigue strength of the tooth surface.

Based on the above-mentioned multi-objective optimization design model, this paper uses MATLAB to realize the dynamic performance optimization for the gear transmission system of the transverse axis cutting reducer (its calculation process is shown in Figure 4).

Table 1 and Figure 5 give the comparison of structural parameters, volume and integrated maximum dynamic load coefficient before and after optimization. So, after the optimization, the volume and dynamic load of the gear system are also decrease obviously. Totally, the volume is reduced by 18.8%, and the integrated maximum dynamic load coefficient is decreased by 11.5%. The results prove that the optimization design carried out in this paper is effective, which can be promoted to solve the dynamic optimization design for complex gear systems.

![Figure 4. Optimization flow chart](image1)

![Figure 5. Comparison of maximum dynamic load coefficients at various stages before and after optimization](image2)
Table 1. Comparison before and after optimization

|        | \(m_i/\text{mm}\) | \(m_{ii}/\text{mm}\) | \(m_{iii}/\text{mm}\) | \(m_{iv}/\text{mm}\) | \(\Phi\) | \(V/\text{mm}^3\) | \(K_{D}^{\max}\) |
|--------|-------------------|---------------------|---------------------|----------------|------|----------------|----------------|
| Before | 10                | 26                  | 10                  | 14             | 1    | 1.2366×10^9   | 3.015          |
| After  | 7.9653            | 21.1691             | 7.6568              | 10.6676        | 0.7742| 1.0037×10^9   | 2.669          |
| Round/Reduction ratio | 8                  | 22                  | 8                   | 11             | 0.8  | 18.8%         | 11.5%          |

5. Conclusions
With the combinations of the ADAMS virtual prototype, multiple linear regression, BP neural network, genetic algorithm, and multi-objective optimization design, the dynamic optimization design for the gear system of a transverse axis cutting reducer is carried out in this paper. The technical line of the dynamic optimization design proposed in this paper starts from the dynamic simulation of the gear system, uses the GA-BP neural network as a bridge to relieve the coupling between dynamic simulation and optimization design, and finally realizes the lightweight design and enhances the stability of the gear system. The technical line and model established in this paper can provide a reference for the dynamic optimization design of some other complex gear systems.

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