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Reliability optimization design of bevel gear drive system based on large-scale double-toothed roll crusher

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Abstract: In this paper, a program for calculating contact strength of tooth surface and dedendum bending fatigue strength of bevel gear is developed. Based on genetic algorithm, the gear reliability is taken as the constraint condition. The global optimization design model of bevel gear reliability is established with the optimization objective on minimum total volume of bevel gear. Taking the large-scale double-toothed roll crusher as an example, the application of the reliability optimization program combined with the discrete element is introduced in detail. Finally, the optimization results that accord with the actual working conditions are obtained.

1. Introduction

Gear transmission is one of the most common mechanical transmission systems, which is widely used in all kinds of precision machinery. The optimal design of the volume or weight of the gear transmission system under the premise of ensuring the gear transmission requirements has become an important subject studied by many researchers [1-2].

For gear transmission, it is necessary not only to possess sufficient precision and strength, but also to ensure that it can complete its specified functions under the specified working conditions and within a specified time. That is, reliability design. In recent years, researchers have carried out in-depth research on reliability design, and achieved considerable results [3-5].

In this paper, a set of general reliability calculation procedures for contact strength of tooth surface and dedendum bending fatigue strength of bevel gear is developed. According to the specific application requirements, taking the minimum volume of the bevel gear as objective function, the reliability of the gear system is the constraint condition, and the genetic algorithm is used to optimize the design of the bevel gear transmission system. Finally, DEM of double-toothed roll crusher is established and the above calculation program is applied for analysis.

2. Calculation of Reliability of Gear Transmission System

According to China Mechanical Design Manual [6], reliability design is to treat the design variables such as load, strength and their influencing factors as random variables, and apply reliability theory and method to make the designed products meet the expected reliability requirements. In this paper, the reliability design of the bevel gear transmission system mainly includes: reliability of surface contact fatigue strength of pinion gear, reliability of surface contact fatigue strength of gearwheel, reliability of dedendum bending fatigue strength of pinion gear and reliability of dedendum bending fatigue strength of gearwheel, which represent as R_1, R_2, R_3, R_4 respectively.

Gear no failure fatigue condition is that the stress on the gear is not greater than the fatigue strength. Reliability is calculated as the probability of no fatigue failure of the gear, as represented by Equation 1.

$$R = P\left\{\sigma < \sigma_H\right\} \tag{1}$$

Where, σ is stress of gear, σ_H is fatigue strength gear.

The mean value of the rated tangential tooth force at transverse pitch is

$$\bar{F}_t = \frac{2000\bar{T}}{d_1} \tag{2}$$

where, $\bar{T}$ is the name torque of the pinion transmission, obtained by experiment or simulation. $d_1$is large end diameter of small bevel gear, and geometric parameters of the transmission of the bevel gear are shown in Figure 1.

The reliability of bevel gear fatigue strength can be calculated by the method of variation coefficient. Assume that both stress and strength obey the normal distribution. The reliability calculation method is shown by Equation 3.

$$R = \Phi\left(Z_R\right) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{Z_R} \mathrm{e}^{-\frac{x^2}{2}}\mathrm{d}x \tag{3}$$

Where, Z_R is connection coefficient.

3 Problem statement

3.1 Objective function

The objective function $F_{obj}$is the minimized or maximized amount that is obtained in the search space under constraints. F_{obj}in this paper is the minimum amount of the total volume of gearwheel and the pinion, which is defined by the following formula

$$F_{\text{obj}} = F_1(m_n, z_1, \varphi_R) + F_2(m_n, z_1, \varphi_R) = \frac{\pi u\left(z_1 m_n\right)^3}{12\times 10^9}\left(1-\left(\frac{z_1-\varphi_R/u}{z_1}\right)^3 + u - u\left(\frac{z_1-\varphi_R}{z_1}\right)^3\right) \tag{4}$$

3.2 Determine constraints

3.2.1. Constraints of independent variables

By constraining the range of the independent variables, the search space can be optimized to find the optimal solution to the optimization problem in the effective area. In the bevel gear volume optimization process, the effective design variables are the bevel gear module number, the number of teeth of the pinion gear and the tooth width coefficient, which can be expressed by Equation (5).

$$\begin{cases} 1 \le m_n \le 50 \\ z_{\min} \le z_1 \le 44 \\ 1/4 \le \varphi_R \le 1/3 \end{cases} \tag{5}$$

3.2.2. Constraints of control variables

The contact fatigue strength of tooth surface and dedendum bending fatigue strength of the bevel gear in the gear drive system of the double-toothed roll crusher need to reach a certain degree of reliability. The manual of Chinese mechanical design stipulates that failure of high parameter, long term continuous operation and long term maintenance (or short design requirement and high reliability requirement) may cause serious economic losses or safety accidents. So set up

$$R_1, R_2, R_3, R_4 \ge 0.99 \tag{6}$$

3.3 Method and design

Genetic algorithm is to search for the optimal solution by simulating the evolutionary process of natural species. Compared with the traditional search method based on gradient, it has the advantages of global search and universality. So genetic algorithm is used in this paper. The volume optimization programming is achieved by the genetic algorithm module in MATLAB software toolbox.

Using graphical user interface (GUI) developed by MATLAB, the designed graphics is saved in a FIG resource file, and then matched with the reliability-optimized design M program file, which links the optimization program with the graphical interface. Finally, an exe-formatted file with independent executable optimization design is generated.

The designer only needs to input the original parameters (Table 1) into the software interface, and the program will automatically calculate the optimal results.

Table 1. Original input parameters

Name	Symbol	Name	Symbol
Motor power	*P* (kW)	Working years	*WY*(year)
Motor speed	n_0 (*r*/min)	Lubricating oil viscosity	*v*50(mm^2/s)
Transmission ratio	*u*	Hardness	*Hard*
Manufacturing accuracy	*PRC*	Material and heat treatment	*Mart* (HRC\HV\ HB)
Support method	*Support*	Scale of production	*Scale*
Usage	*Ut*	Reliability requirements	*Reliability*

4 Application

Take the bevel gear transmission system of the large double-toothed roll crusher designed by Taiyuan Heavy Industry as an example for application analysis. The main motor power P = 710kW, motor speed n = 1500r/min. Shaft angle is 90 degrees, pinion cantilever support, large gear support at both ends. Manufacturing accuracy is 6 grades, expected working life is 10 years. The pinion material is 20CrMnMo, carburized and quenched, and the tooth surface hardness is 56~62HRC. The material of gearwheel is 42CrMo, quenched-tempered heat treatment, and the hardness of gear surface is 250~300HBW. No. 100 extreme pressure gear oil is used. Production scale is in batch.

4.1 DEM simulation

This paper uses EDEM to establish the discrete element model of the double-toothed roll crusher: the establishment of the crushing material coagulation model, the establishment of the operation model of the double-toothed roll crusher and the establishment of the particle plant. The crusher material is steel, and the particle material is coarse sandstone. The material is set as table 2.

Table 2. Material parameters

Material	Steel	Coarse sandstone
Density(kg/m3)	7850	2500
Poisson's ratio	0.3	0.28
Shear modulus(Pa)	7.9×10^{10}	2.7×10^{8}
Coefficient of restitution	0.5(Steel- Coarse sandstone)	0.2(Coarse sandstone - Coarse sandstone)
Static friction	0.3(Steel- Coarse sandstone)	0.4(Coarse sandstone - Coarse sandstone)
Rolling friction	0.01(Steel- Coarse sandstone)	0.01(Coarse sandstone - Coarse sandstone)

The radius of broken particle is 300mm, which is formed by agglomerating particles with a radius of 40mm. The agglomerated radius is set to 40.5mm. The agglomeration model is shown in Figure 2.

The geometric model of the double-toothed roll crusher was introduced into the EDEM. The rotation speed was set to 30 rpm. The particle parameters were set according to the above and the corresponding factories was established. The simulation process is shown in Figure 3. Torque information is shown in Figure 4.

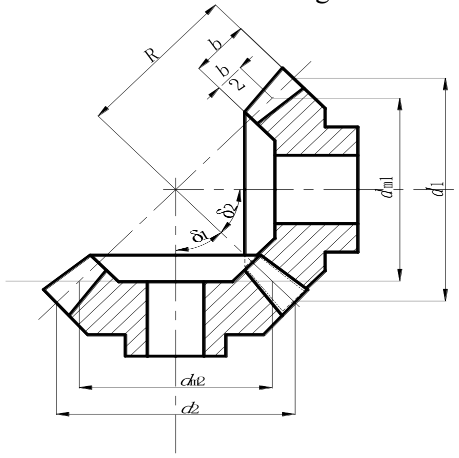
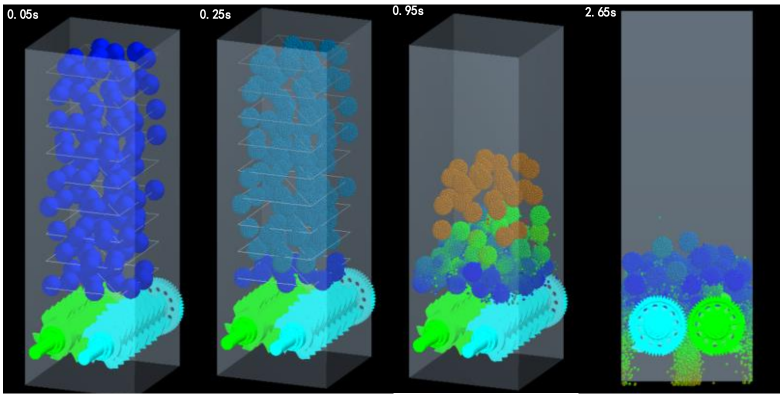
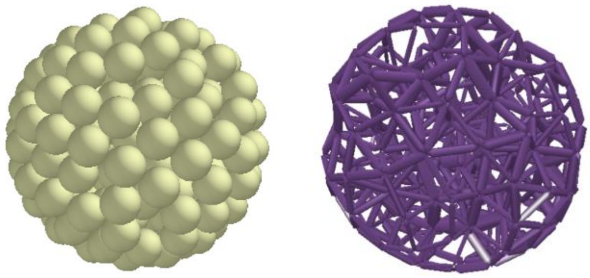


Figure 1. Bevel gear transmission geometric parameters



a) Particles generation b) Particle replacement c) Particle drop accumulation d) Particle breakage

Figure 3. Discrete element simulation process of double-toothed roll crusher



a) b)

Figure 2. Particle agglomerate model
(a) Particle model; (b) Cohesive bond model

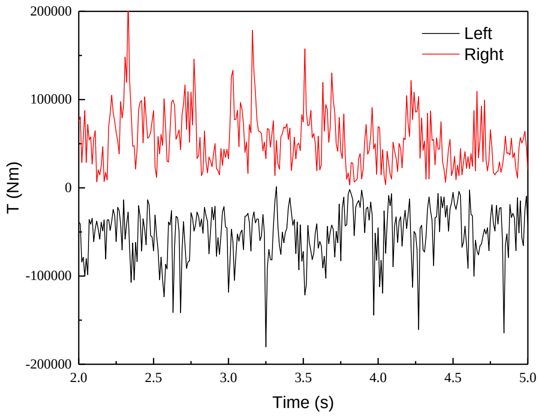


Figure 4. Roller shaft output torque

Take the stable stage of torque, and calculate the mean and standard deviation of the torque. The result is taken as the average value of the two axes.

$$\begin{cases} \overline{T}_e = \dfrac{\overline{T}_{\text{right}} + \overline{T}_{\text{left}}}{2} = \dfrac{56814.26 + 59913}{2} = 58363.63\text{N}\bullet\text{m} \\ \delta_{T_e} = \dfrac{\delta_{T_{\text{right}}} + \delta_{T_{\text{left}}}}{2} = \dfrac{37297.05 + 38519.47}{2} = 37908.26\text{N}\bullet\text{m} \end{cases} \tag{7}$$

4.2 Data Processing and Optimization

The variation coefficient of the tangential force V_{F_t} is the same as the variation coefficient of the working axis torque V_{T_e}.

$$V_{F_t} = V_{T_e} = \frac{\delta_{T_e}}{\overline{T}_e} = \frac{37908.26}{58363.63} \approx 0.65 \tag{8}$$

Input calculation results into the auxiliary software, and the running program gets the optimization results as shown in Table 3.

4.3 Analysis of optimization results

Table 3 is the result of the conventional optimization design (The constraint condition is that the tooth surface contact stress and dedendum bending stress are within the allowable stress range.) and reliability optimization design (before and after the discrete element simulation).

Table 3. Optimized design results

	m_n	z_1	φ_R	F_{obj}	R_1	R_2	R_3	R_4
Routine	20	12	0.33	0.035	0.97	0.77	1	1
Before DEM	11	32	0.33	0.103	1	1	0.994	0.99
After DEM	11	35	0.33	0.146	1	1	0.994	0.99

It can be seen from table 3, compared with the reliability optimization design, the gear obtained by conventional optimization design is relatively small. This is because the gear strength requirement is met, and the effect of gear fatigue stress on the failure of bevel gear is not considered. At the same time, the reliability of the conventional design result gear is low, especially R_2, less than 0.8.

The results of two reliability optimizations are basically similar. The number of teeth using the discrete element simulation results is more, indicating that the total gear volume is larger and the design is more secure. This is because the tangential force of the gears is a random variable, but the coefficient of tangential force variation in empirical design is obtained by constant value, so the value is small. The torque generated by the discrete element simulation is in a fluctuating state, which is closer to the actual working condition, and the coefficient of variation is greater, so the optimized results obtained are more secure.

5 Conclusion

The optimization goal is to minimize the total volume of the bevel gears. Using the reliability calculation formula instead of the traditional stress and strength as constraint conditions for global optimization design, the result can ensure the performance of long-time running machines is safer and more reliable.

In the calculation of reliability, using the self-design MATLAB auxiliary software, the user or designer only needs to input the original parameters in the software interface to get the optimal results. It saves the complicated calculation formula and the process of consulting various handbooks, thus greatly saving the design time and the optimization time.

Taking the $2PGC1040\times3610$ large double-toothed roll crusher designed by Taiyuan heavy industry as an example, the program of reliability optimization design is verified. By comparing with the traditional optimization method, the superiority and practicability of the reliability optimization design are analyzed. The more practical results are obtained by combining the discrete element simulation of the model.

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