Fault simulation and forecast of helical cylindrical gear of reducer based on ADAMS

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Abstract. Aiming at the problems that the dynamic speed and meshing force of the helical cylindrical gear of the reducer are difficult to actually measure and the test cost is high, the helical cylindrical gear transmission system of a crane reducer is used as the research object, and the 3D modeling software SolidWorks is used to establish the assembly model of the gear transmission system, import the dynamic simulation software ADAMS to establish simulation model, and perform simulation analysis on it. The simulation results show that the gear speed is stable after acceleration, which is basically close to the theoretical calculation value; meshing at different multiples the gear meshing force amplitude is different at different frequencies. As the frequency multiplier increases, the amplitude shows a downward trend. Finally, Ensemble Empirical Mode Decomposition (EEMD) sample entropy and Extreme Learning Machine (ELM) are used for fault prediction to verify the effectiveness of this method. The above can provide a certain reference basis for the condition monitoring and fault prediction of the gearbox of metallurgical cranes, so as to ensure the safe operation of the crane.

1. Introduction

Gearbox is an important part of mechanical transmission. In the failure of gearbox, the fault of gear occupies a large proportion, so the fault diagnosis of gearbox has important research significance. For gearbox fault diagnosis research, due to the high cost of a complete set of vibration test equipment, the applicability is not good, in most cases, the fault diagnosis of gearbox is analyzed by computer simulation.

Aiming at the gearbox simulation model, Inalpolat [1, 2] et al. proposed a time-varying dynamics model to predict the modulation sidebands of the planetary gear mechanism. Literatures [3, 4] uses the advantages of Adams dynamic simulation analysis to study the dynamic force of the gear shaft of the planetary gearbox. Reference [5] combined Adams and Simulink models to study the current characteristics of generator sets under gear broken tooth faults. Eritenel et al. [6] established a three-dimensional model of a single-stage planetary gear system and analyzed the inherent characteristics of the system. Abbes et al. [7] analyzed the influence of eccentricity and crack failure on the dynamic characteristics of the gear system through the finite element model of the fixed-axis gear system. MA et al. [8] calculated the time-varying meshing stiffness under different crack depths through the fixed-axis gear train finite element model, and studied the vibration signal characteristics of different crack faults. However, the above literature only studies the vibration characteristics of the gear transmission system under a single gear failure, and does not compare and analyze different gear failures.
For gear fault identification and prediction, Amir Ali Tabatabai Adnani et al. [9] through Empirical Mode Decomposition (EMD) and Hillbert transform, develop a code in Matlab in order to detect the presence of the fault the frequency spectrum of IMF's is created and defect is detected in gearmesh frequency of the spectrum. Wang Jingyue et al. [10] In this paper, a compound fault diagnosis method based on Nonlinear Mode Decomposition (NMD) and Teager energy operator demodulation was proposed and applied to pitting compound fault diagnosis of gear transmission system. Han Hongzheng et al. [11] improved lumped parameter gear dynamic model was established based on fracture mechanics theory. Zong Meng et al. [12] Considering the influence of spalling of different widths, lengths and positions on the time-varying meshing stiffness of the gear, a six-degree-of-freedom gear dynamics model was established. Junchao Guo et al. [13] a fault detection method of planetary gearbox based on Enhanced Average (EAVG) filter and Modulated Signal Bispectrum (MSB) is proposed. The simulation results prove the feasibility of EAV-MSB in state monitoring and fault diagnosis of planetary gearbox. Xianhua Chen et al. [14] the dynamic characteristics of a planetary gear system with crack faults were studied by considering the effects of gravity, bearing clearance, gyroscope and centrifugal force.

In view of the shortcomings of the above models, this paper takes a certain type of metallurgical crane gearbox as the research object, realizes the three-dimensional modeling and virtual assembly of the reducer based on SolidWorks platform. On this basis, the multi-body dynamics rigid flexible coupling model of the reducer is established by using ADAMS, the variation law of output speed and meshing force is obtained, and the frequency spectrum analysis is carried out, which provides some reference for the reliability, vibration characteristics and optimal design of the system.

2. Establishment of dynamic model of gearbox

2.1. Establishment of 3D model

Parametric modeling is carried out in the 3D Modeling Software Solidworks, and the virtual assembly is carried out to generate the solid model. The basic parameters of gears are shown in Table 1.

| Gear  | Modulus | Number of teeth | Pressure angle | Tooth width | Helix angle |
|-------|---------|-----------------|----------------|-------------|-------------|
| Gear 1 | 10      | 18              | 20°            | 200mm       | 8°          |
| Gear 2 | 10      | 92              | 20°            | 200mm       | 8°          |
| Gear 3 | 18      | 17              | 20°            | 300mm       | 8°          |
| Gear 4 | 18      | 70              | 20°            | 300mm       | 8°          |

In this paper, the model is simplified as follows without affecting the accuracy of the simulation results [15, 16]: a) during assembly, the upper and lower boxes are directly fixed instead of bolt connection, and the upper and lower boxes are regarded as a whole; b) the gear and shaft are directly fixed instead of key connection; c) the assembly clearance and meshing clearance between the transmission components are ignored; the assembly clearance and meshing clearance between the transmission components are ignored; d) The bearing is simplified to a cylinder of the same volume and mass. The gearbox studied in this paper is a two-stage reduction transmission, so the probability of high-speed pinion failure is large. Cracks, broken gear and wear faults are set in advance at the high-speed pinion, as shown in Figure 1.

2.2. Establishment of dynamic model

In the 3D Modeling Software Solidworks, save the copy as Parasolid format with the extension of *.X_T rigid body file imported into the simulation software ADAMS. Considering that only the acceleration map of the mass center can be obtained in the simulation of pure rigid body, and the accurate fault information can't be extracted, so it is necessary to introduce flexible body [17]. In this paper, the gear 1, shaft 1 and box are flexible. The box is imported into ANSYS software, and the modal neutral file in MNF format is established and exported. The box rigid body in ADAMS is replaced. At the same time, the gear 1 and shaft are flexible in Adams directly. Thus, the dynamic model with both rigid and
flexible body is rigid flexible coupling dynamic model. According to the motion relationship between the components, the constraints are carried out by rotating pair, fixed pair and contact pair, as shown in Table 2.

![Figure 1. Faulty gear.](image)

**Table 2.** Constraints between components.

| Types of kinematic pairs | First part          | Second part          |
|--------------------------|---------------------|----------------------|
| Rotating pair            | Shaft 1, Shaft 2, Shaft 3 | Ground               |
|                          | Shaft 1, Shaft 2, Shaft 3 | Bearing              |
|                          | Gear 1              | Axis 1               |
|                          | Gear 2, Gear 3      | Axis 2               |
| Fixed pair               | Gear 4              | Axis 3               |
|                          | Bearing             | Box                  |
| Contact                  | Gear 1              | Gear 2               |
|                          | Gear 3              | Gear 4               |

3. **Parameter setting**

3.1. **Selection of contact force parameters**

In this paper, the indirect contact force of gears is analyzed, so the meshing transmission of gears is simulated by adding collision contact force, and the "impact function method" is selected to calculate the contact force, i.e. the meshing force [18]. The parameters in the impact function method are set as follows:

1. The stiffness coefficient \( k \). The contact stiffness \( k \) between the two sets of gears is calculated according to Hertz contact theory, the contact stiffness of the high-speed and low-speed gears is \( 1.33 \times 10^6 \, \text{n} \cdot \text{mm}^{-1} \), \( 1.70 \times 10^6 \, \text{n} \cdot \text{mm}^{-1} \), respectively.

2. Damping coefficient \( C \). The damping coefficient represents the loss of kinetic energy in the mechanical system. The greater the damping coefficient, the greater the kinetic energy loss of the mechanical system. Based on the stiffness coefficient, the damping coefficient is generally 0.1% ~ 1% of the stiffness coefficient.

3. Force index \( e \). The force index \( e \) reflects the nonlinear relationship between contact force and deformation. According to Hertz contact theory, the value of force exponent \( e \) is 1.5.

4. Embedding depth at maximum damping \( d \). The embedding depth \( d \) at the maximum damping refers to the maximum distance between the two objects when they contact each other. If it is set too much, it will lead to real embedding in the meshing process. If it is set too small, the calculation result will be wrong. According to experience and repeated tests, the value in this paper is 0.1mm.

5. Combined with the relevant Literature [19] and the material and lubrication mode of gear [20], the relevant parameters of Coulomb friction are as follows: dynamic friction coefficient \( \mu_{\text{d}} = 0.05 \), dynamic sliding speed \( v_d = 10 \, \text{mm/s} \), static friction coefficient \( \mu_{\text{s}} = 0.08 \), static sliding speed \( v_s = 0.1 \, \text{mm/s} \).
3.2. Selection of simulation parameters
In the simulation, the high-speed shaft speed is set to 1800r/min, and the load torque is set to 5000N·m. After conversion, the final rotation driving function is step (time, 0,0,2,10800d), and the load torque function is step (time, 0,0,2, - 5000000). In addition, in order to obtain enough data in ADAMS, the simulation time is set to 1s. If the number of simulation steps is too small, the parameter iteration may not converge and the simulation cannot be carried out. Therefore, the simulation steps are set to 10000. WSTIFF is chosen to solve the integrator, which can make the velocity and acceleration satisfy the differential equation of system dynamics. I3 is chosen as the integral scheme, which can monitor the state variable errors of the unique and other differential equations, and the relative speed is relatively fast.

4. Simulation and analysis

4.1. Simulation verification of rigid flexible coupling model
After stable start-up, angular velocity simulation calculation is carried out. The theoretical value of high-speed shaft angular velocity is 10800d/s. Figure 2 shows the curve of high-speed shaft angular velocity. The average value of angular velocity between 0.2s and 1.0s can be calculated as 10802.5d/s, and the error is 0.023% compared with the theoretical value. The error value is small and can be ignored, so the model is verified to be correct.

![Figure 2. High speed shaft angular velocity curve.](image)

4.2. Frequency domain analysis
The frequency domain diagram of vertical contact force of high-speed gear is obtained by FFT, and the frequency domain diagram is compared and analyzed, as shown in Figure 3 normal gear, worn gear, broken gear and cracked gear are respectively shown.

Analysis of Figure 3 and Table 3 shows that:
(1) It can be seen from Figure 3 that the contact force amplitude reaches the maximum value at 540.7Hz, and the error is 0.13% compared with the theoretical meshing frequency 540Hz of high-speed gear, and the difference is small. In the frequency spectrum, there will be a side band, which is located on both sides of the meshing frequency. The difference between the side frequency of 509.2Hz, 571.5Hz and the meshing frequency of 540Hz is 30.8 and 31.5, which is similar to the theoretical frequency f1. It can be basically judged that the fault of high-speed pinion is caused.

(2) The amplitude decreases rapidly at about 2 times, 3 times, and 4 times of the meshing frequency of high-speed gears, indicating that the contact force between gears reaches the maximum at the meshing frequency of the gears, and decreases sequentially at other times. When designing other parts of the gear of the crane reducer, it is necessary to avoid frequencies with large gear meshing force amplitude to prevent the crane reducer from resonating and causing safety problems.
4.3. EEMD sample entropy and ELM fault prediction

Based on the LMD sample entropy and ELM gear fault prediction method proposed by Zhang Ning et al. [21], in this paper, in order to further study the gear fault characteristics, EEMD sample entropy method is used to extract fault features of gear time domain signals and ELM gear fault prediction. EEMD is used to decompose the vertical contact force signal of high-speed gear. As shown in Figure 4, the first six order IMF components obtained from EEMD decomposition of normal gear are shown.

Figure 4. EEMD decomposition results of normal gear.

The sample entropy corresponding to the first six order IMF components of each gear condition is calculated to form the feature vector, and the effective features of each gear working condition are
extracted, as shown in Figure 5. It can be seen from Figure 5 that the values of sample entropy are different under different working conditions, which has good separability. Under normal working conditions, the planetary gearbox runs smoothly with the minimum entropy; after replacing the fault gear, the complexity of vibration signal increases and the entropy value increases; under the condition of Cracked Gear, the sample entropy is the largest, that is, the fault mode is more serious, which is consistent with the results of signal analysis.

![Figure 5. Distribution of EEMD sample entropy.](image)

![Figure 6. True and predicted values of ELM.](image)

40 groups of data were collected for each working condition, and 160 groups of data were obtained from 4 working conditions. Among them, 25 groups of data were randomly selected from each working condition as training samples, and the remaining 15 groups were taken as test samples and brought into ELM. The number of ELM hidden layer neurons n is set to 20, the activation function TF of hidden layer neurons is set to sig, and the application type TYPE is set to 1 (indicating classification). Digital labels are used to represent gear working conditions in the following order: 1~15 are normal gears (label 1); 16~30 are worn gears (label 2); 31~45 are cracked gears (label 3); 46~60 broken gear gears (label 4). As shown in Figure 6, the sample entropy eigenvector obtained by EEMD decomposition failed to predict in 2 out of 60 prediction sample data, and the accuracy rate was 96.6%.

5. Conclusions
In this paper, the rigid flexible coupling modeling of the gear box of metallurgical crane is carried out by SolidWorks and Adams. Through the simulation, the frequency domain diagrams of normal, worn, cracked and broken gear in the vertical direction of indirect contact force of high-speed gear are obtained. The following conclusions are obtained: In the frequency spectrum diagram, the side band is located on both sides of the meshing frequency, and the interval between the side frequency and the meshing frequency is almost the same; the frequency corresponding to the contact force amplitude at the maximum value is basically the same as the theoretical meshing frequency; the amplitude decreases rapidly at 2 times, 3 times, and 4 times of the meshing frequency; the amplitude of the fault gear at the meshing frequency of the high-speed gear is higher than that of the normal gear, The increase rate of the broken tooth fault is the smallest, the crack fault is the largest, and the wear fault is between the two. Finally, the gear fault feature extraction method based on EEMD sample entropy is used to predict the gear fault by ELM.

Acknowledgements
This research was funded by Anhui Science and Technology Major Project (Grant NO: 201903a05020029), the University Synergy Innovation Program of Anhui Province (Grant NO: GXXT-2019-048) and Open Project of Anhui Province Key Laboratory of Special and Heavy Load Robot (Grant NO: TZJQR006-2021).

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