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Analysis of the Wear Mechanism of High-Speed Transmission and the Prediction Model

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Abstract. Wear is an important factor that determines the normal functioning of high-speed transmission. This study aimed to analyze the stress distribution of high-speed transmission using finite element software and the principle of wear reliability. The weak parts where the stress was concentrated were identified. Tests were performed under different conditions using a uniform design. Thus, the major factors influencing the wear prediction model were identified as surface hardness of material, load, and sliding velocity. A mathematical model for wear prediction was then established using the partial least squares method. Experimental verification was performed, and the high precision of the prediction model was confirmed.

Keywords. High-speed transmission, partial least squares method, prediction model, wear

1. Introduction

High-speed transmission mechanism has found wide applications in military and civil fields. One of the most representative applications is the ammunition feed system with a high rate of fire [1]. The high-speed transmission used in the ammunition feed system is a precision, complex product. The reliability of its kinematic accuracy is crucial for the operation of the ammunition feed system. During high-speed firing, the kinematic pair in the transmission undergoes changes in the size and shape of parts due to wear. Friction is the resistance that one surface or object encounters when moving over another. When the contact stress is higher than the yield strength of the material, continuous material loss due to friction occurs [2, 3]. In the study of wear mechanism, Dong Bingwu et al combined with high-speed pendulum bearing testing machine to analyze the wear performance of self-lubricating gasket material [4]. Yang Wenjun et al proposed a mathematical model of mechanical wear condition monitoring based on wear particle feature recognition [5]. Wieczorek Andrzej N et al proposed different models of steel surface wear under two kinds of abrasives based on wear observation [6]. In terms of wear prediction model, Zhao Heming and others analyzed the

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maximum allowable wear of gear transmission mechanism based on ADAMS [7]. Wang Guohui and others established the prediction model of ablation wear of gun barrel based on BP neural network based on genetic algorithm [8]. Chen Yuanling et al established a friction and wear prediction model for the distribution pair of aviation piston pump under the condition of high speed and high pressure [9]. Qin Guohua et al established a neural network prediction model between cutting process parameters and tool wear based on the maximum fusion evaluation index [10]. Most of the previous wear prediction models were derived from the characteristics and wear mechanism of a single mode of wear. For example, Archard [11-13], an English scientist, proposed the wear prediction equation based on the investigation into gear engagement and gear sliding: $W = KSP/P_m$, where W is the wear volume, S is the sliding distance, P is the load imposed, and P_m is the compressive stress encountered by the soft material when flowing.

A chainless transmission was used for the ammunition feed system to ensure the velocity of ammunition feed and the reliability of the ammunition feed mechanism. For example, the rate of fire increases from 850 rounds/min to 6000 rounds/min for a naval gun. At this rate of fire, the speed of relative movement is considerable between the parts, leading to substantial wear of the ammunition feed system. Under some severe situations, jamming of cartridge, reduction in ammunition feed velocity, and suspension of shooting would occur. Therefore, establishing a wear prediction model based on the analysis of the wear mechanism of the high-speed transmission is of high theoretical and practical value.

2. Wear Reliability

Wear reliability involves reliability, friction and wear, material mechanics, mechanical system dynamics, and other disciplines. However, because of the complex mechanical structure, wear reliability research is more difficult. In the study of wear reliability, the cumulative wear and the maximum allowable wear must be determined.

Mechanical wear reliability (P_s) refers to the possibility that the actual wear of the wear pair is within the allowable wear amount in the specified time and under the specified conditions of use. For complex mechanical systems, the reliability can also be expressed as the probability of accomplishing the expected working life. Wear reliability is used to study the reliability of the mechanical system in terms of wear, which is determined by the maximum allowable wear and wear speed. The maximum wear of the system is generally determined by experience or other methods. Different systems and kinematic pairs have different maximum allowable levels of wear. However, the system and the movement of the failure of the components are assessed using the same criteria. It is considered as a failure when the cumulative wear is greater than the maximum allowable wear. For example, in the case of a gear transmission mechanism, the cumulative wear amount of the gear shaft is W_t at time t without considering the wear of the tooth profile, and the maximum allowable wear amount is $W_{\max}$. It is considered as gear transmission failure when $W_t > W_{\max}$. Its reliability can be expressed as:

$$R\left(W_{\max} \mid t\right) = P\left(W_t < W_{\max}\right) \tag{1}$$

Therefore, no matter which kind of kinematic pair is used, the reliability of the damage based on the judgments is consistent. If W_t represents the cumulative wear and $W_{\max}$ represents the maximum allowable wear, then:

$$M_W = W_{\max} - W_t \tag{2}$$

Where M_W is the state variable at the time of wear, that is, the safety margin.

The wear reliability and failure probability state variables can be expressed as:

$$P_S = P\left(M_W > 0\right) \tag{3}$$

$$P_f = P\left(M_w < 0\right) \tag{4}$$

For the prediction of the wear reliability of a moving mechanism, it is necessary to determine the maximum allowable wear and cumulative wear.

In studying the wear reliability of a gear shaft, it is assumed that the tooth profile does not wear out in the gear drive. Then, the wear of the gear shaft causes the gear shaft to become thinner, which in turn affects the center distance of the two gears. As the center distance of the gear is increased, it affects the meshing angle. The coincidence degree of the gear will be less than its allowable level when the gear is worn to a certain extent; i.e., when the cumulative wear reaches a certain value. At this point, the relationship between the center distance and the amount of wear can be obtained using ADAMS software simulation. The amount of wear at this time can be defined as the maximum allowable wear.

The wear of components is affected by the load, sliding speed, surface hardness of materials, and other factors. The cumulative wear is the sum of the mass lost in a certain amount of time.

The wear process is divided into three stages: Stage I is called the run-in stage, and the wear rate is high in this stage. After wear and tear, the surface of the material becomes flattened to form a harder oxide layer, and the wear rate gradually decreases. Stage II is called the stabilization phase. After the run-in phase, the wear will enter a long and stable stage. In this stage, the wear rate is almost constant, the wear amount is linearly related to time, and the wear and tear performance are evaluated through this stage. Stage III is the stage of intense wear. In this stage, after the first two stages of wear accumulation, there is a large change in the wear rate and the surface quality deteriorates. In this stage, components will quickly fail. The intense wear stage and the run-in phase are both very short. Thus, in order to simplify the problem, the analysis in this paper will only discuss the stabilization period. In this way, according to the characteristics of stable wear, in the analysis of sportswear reliability, assuming that the wear and tear are proportional to time, W is used to denote the cumulative wear amount in time t , and $\overline{w}$ is the wear rate, the wear life and wear amount can be calculated by the following equation:

$$W = \overline{w}t \tag{5}$$

In summary, according to equation 5, the cumulative wear can be obtained within time t.

From the previous analysis, we can see that the impact of wear factors is random, which makes the amount of wear a random variable. Moreover, as the wear time increases, the randomness also increases. Assuming that the wear level for smooth wear is a random variable, it is expressed by W_0 and its distribution is $f(W_0)$. The cumulative wear of the system is W and the distribution law is $g(W)$, so W can be expressed as:

$$W = g(W) = g\left[f(W_0)\right] \tag{6}$$

If the wear rate $\overline{w}$ is used to express the amount of wear W, W can be expressed as:

$$W = \int_0^t \overline{w}(t)\,dt \tag{7}$$

Where represents wear time.

If the maximum allowable wear of the kinematic pair is expressed by $W_{\max}$, the reliability of the system is:

$$R(W_{\max} \mid t) = P(W < W_{\max}) \tag{8}$$

The probability of failure is:

$$P_f(W_{\max} \mid t) = \int_{W_{\max}}^{\infty} g(t) d(W) \tag{9}$$

Its reliability is:

$$R(W_{\max} \mid t) = 1 - P_f(W_{\max} \mid t)$$

$$= 1 - \int_{W_{\max}}^{\infty} g(W) d(W) = \int_{-\infty}^{W_{\max}} g(W) d(W) \tag{10}$$

Where $g(W)$ is the probability density function, expressed as:

$$g(W) = \frac{1}{\sigma_W \sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{W - \overline{W}}{\sigma_W}\right)^2\right] \tag{11}$$

Where $\overline{W}$ is the mean of the wear amount and σ_W is the standard deviation of the wear amount.

Thus, according to equations 9 and 10, the reliability of the mechanism to reach the maximum allowable wear is:

$$R(W_{\max} \mid t) = \int_{-\infty}^{W_{\max}} g(W) d(W)$$

$$= \int_{-\infty}^{W_{\max}} \frac{1}{\sigma_W \sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{W-\overline{W}}{\sigma_W}\right)^2\right] d(W) \tag{12}$$

Where $W_{\max}$ is the maximum allowable wear, $\overline{W}$ represents the mean of the wear, and σ_W denotes the variance of the wear.

Wear reliability (P_S) is defined as the probability of the wear amount of a kinematic mechanism falling within the maximum allowable range of wear in a specific time and under specific use conditions [14, 15]. P_S is determined by the maximum allowable amount of wear and rate of wear.

Ignoring the lubricating effect, the rate of wear is jointly determined by three factors, namely, sliding velocity, material hardness, and load. The judgment criterion for the failure of kinematic mechanism is that the cumulative wear amount is larger than the maximum allowable wear amount.

If W_t is the cumulative wear amount and $W_{\max}$ the maximum allowable wear amount, then

$$M_W = W_{\max} - W_t \tag{13}$$

where M_W is the state variable during wear, that is, safety margin.

Then, the wear reliability is expressed as

$$P_S = P(M_W > 0) \tag{14}$$

3. Finite Element Simulation of High-speed Kinematic Mechanism

The large module gear in the transmission is made of 30CrNi2MoVA. The modulus of elasticity is $P = 2.1 \times 10^9$ and the Poisson's ratio is $\sigma = 0.25 \sim 0.3$.

Considering that the function of ADAMS software in modeling is relatively weak, and it has a direct interface with 3D modeling software Pro/E, this paper uses Pro/E software to model the gear, and the established gear model is shown in figure 1. After the model is established according to the gear parameters, the model is imported into AMAMS software, and the material and quality information of the gear is defined by AMAMS software. After dynamic simulation, the history curve of gear force and time is obtained, as shown in figure 2. It can be seen from figure 2 that the stress concentration occurs in the tooth profile and root, and the average force is about 1923.548N.

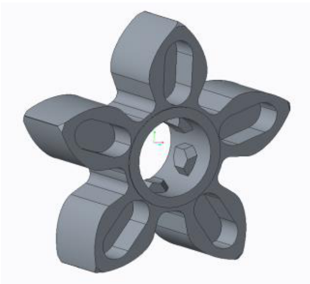

Figure 1. Large module gear built using the Pro/E software.

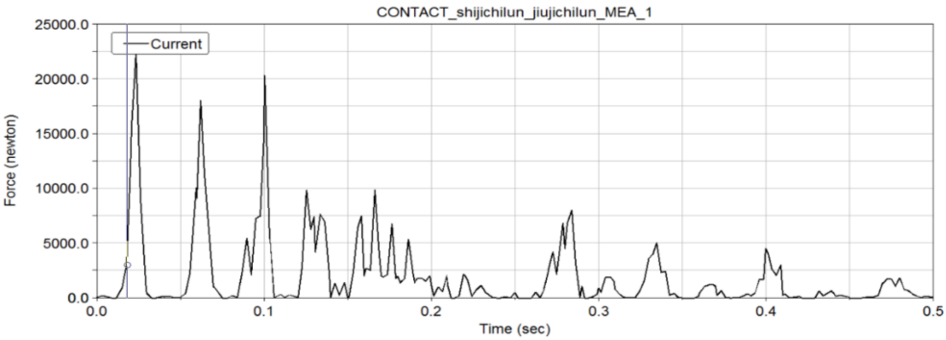

Figure 2. Stress curve of gear over time.

Different parameters of the large module gear are shown in Table 1.

Table 1. Parameters of the large module gear.

Gear parameter	Symbol	Drive gear	Driven gear
Module	m	18	18
Number of teeth	Z	5	5
Profile angle of a gear	A	20°	20°
Addendum coefficient	h_a^*	1.176	1.118
Modificatio coefficient	X	0.3046	0.426

4. Friction and Wear Experiment of High-Speed Kinemate Mechanism

The friction and wear experiments of high-speed kinematic mechanism were performed to obtain the wear amount considering different influence factors.

According to the actual operation of the high-speed transmission, the specimen used for the friction and wear experiment was made of 45# stainless steel. The parameters of thermal treatment of the specimen are shown in Table 2. The counter pair is illustrated in Figure 3.

Table 2. Parameters of thermal treatment of the specimen.

Specimen no.	Material	Thermal treatment
1	45# Stainless steel	Normalization at 600°C, air cooling for 60 min
2	45# Stainless steel	Normalization at 550°C, air cooling for 60 min
3	45# Stainless steel	Normalization at 500°C, air cooling for 60 min
4	45# Stainless steel	Normalization at 450°C, air cooling for 60 min
Counter pair	30CrMnSi	Annealing at 800°C, water cooling

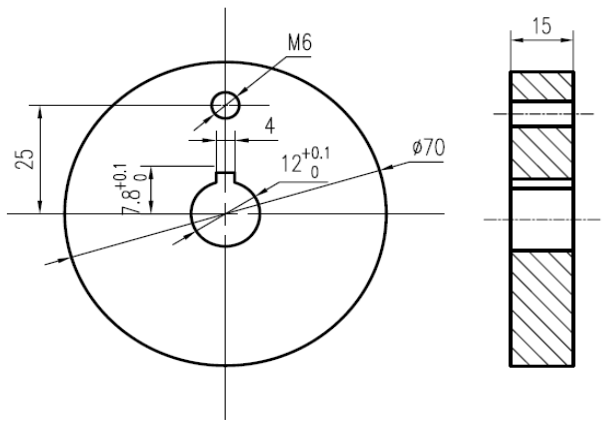

Figure 3. Illustration of the counter pair.

According to the material, contact force, and sliding velocity of the friction pair, the factors considered in the experiment and the levels of each factor were as follows:

Surface hardness of material: 241, 282, 314, and 366 HV

Load: 100–430 N, with 12 levels

Rotational speed: 50–380 r/min, with 12 levels

Time: 30 min

The parameters of the friction and wear experiment are shown in Table 3.

Table 3. Parameters of the friction and wear experiment.

No.	Hardness (HV)	Load (N)	Rotational speed (r/min)
1	241	160	140
2	241	250	260
3	241	340	380
4	282	430	110
5	282	130	230
6	282	220	350
7	314	310	80
8	314	400	200
9	314	100	320
10	366	190	50
11	366	280	170
12	366	370	290

Figure 4. Surface morphology under the load of 130 N, rotational speed 230 r/min, and hardness 282 HV.

The surface morphology of the specimen was observed under the microscope after the experiment. The specimen surface exhibited severe plastic deformation, with the presence of many abrasive specks of dust, which was typical of adhesive wear, as shown in Figure 4.

A large number of grinding cracks and grooves were seen on the specimen surface, which was also typical of abrasive wear, as shown in Figure 5 (load 190 N, rotational speed 50 r/min, and hardness 366 HV).

Figure 5. Surface morphology under the load of 400 N, rotational speed of 200 r/min, and hardness of 314 HV.

Therefore, the wear of the high-speed transmission was the combined result of adhesive and abrasive wear.

5. Wear Prediction Model of High-Speed Transmission

The experimental data fluctuated considerably, and the random error was large due to the randomness of the wear process. Therefore, the measurement of wear amount was of a statistical nature. In this study, a uniform design was adopted, and a stepwise regression was conducted on the experimental data. The wear prediction model was built using the partial least squares method.

When building the wear prediction model, x_1, x_2, and x_3 were the three major influence factors of the wear amount, namely, surface hardness of material, load, and sliding velocity.

The quadratic polynomial model built using the uniform design was as follows:

$$y = a_0 + \sum_{i=1}^{3} a_i x_i + \sum_{i=1}^{3} a_{ii} x_i^2 + \sum_{i<j} a_{ii} x_i x_j + \varepsilon \tag{15}$$

where a_0, a_i, a_{ii}, and a_{ij} are coefficients of regression; ε is a random error; and i is the number of influence factors.

After statistical treatment, the quadratic polynomial model based on partial least squares method was derived as follows:

$$\begin{aligned} y &= 15.005778 - 0.024578x_1 + 0.009331x_2 + 0.003675x_3 \\ &-0.000046x_1^2 + 0.0000223x_2^2 + 0.000006x_3^2 \\ &+0.000012x_1x_2 + 0.000005x_1x_3 + 0.000007x_2x_3 \end{aligned} \tag{16}$$

The residual sum of squares was 4.5153, indicating that the fitting results satisfied the precision requirement.

Using Eq. (16), several predicted values of the wear amount were calculated and compared against the test values, as shown in Table 4.

Table 4. Comparison of predicted and test values of wear amount.

Variable	**Comparison**				
	1	**2**	**3**	**4**	**5**
x_1 (HV)	241	241	282	314	366
x_2 (N)	160	250	430	310	190
x_3 (r/min)	120	260	110	80	50
Test value (mg)	7.77	11.17	18.80	9.80	3.13
Predicted value (mg)	9.89	12.99	14.97	9.59	3.62
Relative error (%)	27.28	16.29	20.37	2.14	15.65

Table 4 shows that the error of the predicted wear amount was small under the aforementioned conditions. This indicated the reliability of the wear prediction model.

6. Conclusion

This novel study analyzed the wear reliability and conducted a finite element simulation of a high-speed transmission. The regions of stress concentration and mean stress values were determined. For the weak parts, friction and wear experiments under different conditions were formulated using the uniform design. The influence factors of the wear prediction model were identified based on the experimental data. Next, the mathematical model for wear prediction was built using the partial least squares method under the three influence factors, surface hardness of material, load, and sliding velocity. The predicted results were compared with the test results. The prediction of wear amount had a small error and high precision.

In this paper, the wear prediction method of high-speed transmission mechanism of a certain bullet supply system based on stepwise regression analysis has little difference within the range of relative error in the prediction process. Compared with the traditional prediction methods, this kind of method is more efficient and accurate.

Finally, we will also proceed from some aspects, such as redesigning gear parameters, modifying material matching, controlling gear processing quality and improving lubrication conditions. It is believed that this has reference significance for improving the working environment of the transmission mechanism and solving the problem of tooth surface wear. In the future, the establishment method of wear model should be deeply studied in order to establish a more complete and accurate model.

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