Prediction and Experimental Validation of Aviation Floating Involute Spline

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Abstract: Based on the research on the wear mechanism of floating involute spline coupling, combined with the traditional Archard wear equation, a wear prediction model of aviation floating involute spline coupling was established. The transient simulation of spline coupling with floating distances of 0 mm, 0.3 mm, and 0.6 mm was carried out using Abaqus, and the accuracy of the theoretical model was verified by analyzing the wear and failure parts of the spline coupling. The analysis results show that there is oxidation wear, adhesive wear, abrasive wear, and other wear forms on the tooth surface of the aviation floating involute spline coupling. Under the influence of the floating distance of the spline coupling, the calculation results are closer to the actual working situations. In addition, with increasing floating distance, the wear depth of the tooth surface increases significantly, and the wear depth becomes larger and larger along the floating end. The above study provides a theoretical basis for designing and maintaining aerospace involute spline couplings.

Keywords: Archard equation; floating distance; involute spline coupling; wear; finite element

1. Introduction

The involute spline connection can meet the connection requirements of large torque and high speed. It is widely used for shaft-to-shaft connections in aerospace driveline systems because it is assembled in a way that ensures shaft guidance and alignment. In the aviation transmission system, there are usually two ways to connect the shaft to the involute spline coupling; one is fixed, and the other is floating. When the spline pair of a floating connection transmits torque, due to the existence of the tooth side clearance, there is a slight relative movement between the inner and outer splines. On the other hand, the axial floating of the spline is caused by the existence of an axial force or the change of external load. Under the combined action of these two relative displacements, the aeronautical gradual floating open-line spline coupling has extremely serious wear and failure. X Z Xue et al. [1,2] used the finite element method to analyze the aviation floating gradual opening. The wear conditions of the linear spline coupling are studied under different tooth surface wear factors, loads, and operating cycles, and a plane spline coupling structure that can simulate the floating involute spline coupling is designed to verify the theoretical research. Since the axial floating distance is one of the key factors affecting the wear of floating involute spline pairs; therefore, exploring the wear conditions of aeronautical floating involute spline pairs under different floating distances has important guiding significance for the design of high-precision, high-strength, and high-reliability involute spline pairs required by advanced aeroengines.

At present, many scholars have studied the wear mechanism of spline coupling. Z L Song et al. [3–5] used the Archard wear calculation formula to obtain the wear depth of the spline coupling within the simulation time. Zheng et al. [6] used the MATLAB–Abaqus joint development method to study the depth of wear of the spline coupling tooth surface. Chen et al. [7,8] studied the wear behavior of spline couplings under various misalignment
conditions through experiments and studied the wear of spline couplings with different materials and different heat treatment methods for the tooth surface. Hu et al. [9,10] studied the depth distribution of the wear of the tooth surface under the condition of compound misalignment of the spline coupling. Zhao et al. [11–13] studied the wear of aviation involute spline couplings under vibration based on the traditional Archard wear calculation formula. Ratsimba et al. [14] proposed a method to predict the fretting wear of spline couplings based on the Archard model. McColl et al. [15] proposed a finite element method to calculate fretting wear based on the modified Archard equation; it simulates the wear process of the pin–disk structure. In addition, the Archard wear formula is often used to calculate the wear of the tooth surface of involute spline couplings, and the model in the research content is also simplified. Therefore, the existing Archard wear formula is unsuitable for gradual floating in aviation and the calculation of the wear depth of the spline coupling.

At the same time, as the basis for calculating the wear of spline couplings, many studies have focused on the contact characteristics of spline couplings. Hong et al. [16] studied the changes in the stress distribution on the tooth surface of the spline coupling under different helical gear helical angles to obtain the optimal helical gear helical angle. Tjernberg et al. [17] established an analysis model to study axial load distribution and torque transmission and concluded that modifying the spline teeth in the axial direction can make the axial load of the spline coupling evenly distributed. Barrot and Paredes et al. [18] also studied the axial torque transmission of the spline coupling and concluded that the main factor affecting the wear of the spline coupling is the distribution of the axial torque. Ding et al. [19] analyzed the slip distance and contact pressure under different conditions. This study laid a good foundation for the research on the wear of aviation spline couplings. Medina et al. [20] studied the elastic contact model of spline couplings based on the boundary finite element method. Cuffaro et al. [21] used numerical analysis models and experimental methods to study the stress distribution of spline couplings and verified it with finite element simulation. Leen et al. [22] analyzed the effects of tooth profile modification on the spline tooth’s surface contact stress, slip distance, and friction factor. The research objects of the above studies are all fixed spline couplings, and the influence of floating distance is not considered. Xiao Li et al. [23,24] investigated the wear fatigue damage model of the floating spline considering the wear effect; the cumulative damage distribution law of fretting fatigue of the axial misalignment and the angular eccentric lower surface of the tooth was analyzed, and the life of the floating spline was predicted.

There is almost no research on the wear of axial floating distance aviation spline couplings. In view of the aviation floating involute, the wear failure of the spline coupling has caused great damage to the aviation transmission system and caused a serious threat to the safety of the whole machine. Therefore, based on the traditional Archard model, this work proposes a wear calculation model for aviation axial floating involute spline coupling with axial floating distance. The contact stress and relative slip rate between the teeth were investigated with axial floating distances of 0 mm, 3 mm, and 0.6 mm. Then, the distribution law of the wear depth along the axial and radial directions was studied. Finally, the theoretical results were verified by the experimental results of the wear depth of the tooth surface of the floating spline coupling. This work provides a theoretical basis for designing and maintaining the involute spline coupling in aviation.

2. Research on the Wear Mechanism of Aviation Floating Involute Spline Coupling

Through the observation and analysis of a large number of scrapped aviation involute spline couplings, the surface topography of some typical abrasion and failure spline couplings is shown in Figure 1. There are many small pits formed by wear in Figure 1a, the analysis here shows that the wear form of the spline coupling tooth surface is mainly fretting wear. In Figure 1b, we can see the corrugated relief, indicating that the wear form here is mainly oxidative wear. In Figure 1c,d, it can be seen that the tooth surface has oxidized wear and adhesive wear. Particles adhere to the tooth surface, forming scratches
during the working process of the spline coupling. In addition, it can be observed in Figure 1e that cracks have formed on the tooth surface of the spline coupling, indicating that the main form is fatigue wear. In Figure 1f, the existence of large pits can be seen; these are the pits formed by the large material of the spline coupling being worn away under the action of adhesive wear. This will seriously affect the roughness of the spline coupling’s tooth surface. This further intensifies the wear of the spline coupling.

Figure 1. Surface topography analysis result of spline coupling: (a) small pits formed by wear; (b) corrugated relief; (c,d) abrasive particles adhered to the tooth surface, forming scratches; (e) cracks on the tooth surface; (f) tooth surface with a large pit.

Combined with the above analysis results of the wear of the tooth surface of the scrapped aero involute spline, as well as the three operating conditions of takeoff, cruise, and landing experienced by the helicopter involute spline, the wear mechanism of the helicopter floating aero involute spline can be derived as follows:

1) Take-off state

When the helicopter is in the takeoff phase, the aircraft’s power system has maximum afterburner in the state, the vibration frequency of the spline coupling increases, and the input torque of the spline coupling is alternating. The alternating external load constitutes the external excitation of spline secondary vibration. The time-varying nature of the comprehensive meshing stiffness introduced by the change in the number of meshing teeth and the geometric errors caused by manufacturing and installation constitute the internal excitation of the spline vibration. This kind of nonlinear vibration of the spline coupling, which exists in extreme working conditions, is caused by the combined action of internal and external excitation, which makes the relatively static contact surface of the two splines of the original design produce obvious slight motion, and the repeated action of micromotion. On the one hand, the contact surface produces fretting wear. The temperature during its operation increases and the lubricating oil in the contact area is forcibly squeezed out, resulting in poor lubrication conditions. The deformation of the tail shaft makes the inner and outer splines designed to move axially produce a relatively large sliding distance of the spline, leading to serious abrasive wear between the contact surfaces of the spline. Sliding caused by deformation of the tail shaft is more intense. This will wear off the surface of the key tooth after fretting wear, and the spline coupling temperature change in the movement process causes the adhesion effect, and the adhesion node formed
by this effect will shear and fracture with the relative slippage of the friction pair surface, which makes the surface and subsurface of the movement spline coupling produce a lot of adhesive wear; metal migration occurs, and separation of metal particles occurs. These separated metal particles act as abrasive particles, which promotes and accelerates the appearance of more furrows on the contact surface of the spline coupling at this stage, so the abrasive wear phenomenon is aggravated. Therefore, spline wear is mainly in the form of abrasive wear, adhesive wear, and fretting wear at this stage.

(2) Cruise state

When the aircraft is cruising, the spline coupling is in a steady-state working environment, and the phenomenon of abrasive wear is reduced. However, spline coupling is still dominated by adhesive wear and abrasive wear due to its complex working conditions and manufacturing and processing errors. The micromovements inside and outside the spline are inevitable; there is still micromovement wear at this stage. However, as a result of the effect of lubricating oil and the above three forms of wear, there is also oxidative wear. This is due to the wear of the key teeth during the takeoff phase, which makes the contact area of the key teeth larger, resulting in close contact of the key teeth involved in the contact, making it difficult for the oxide wear debris generated by oxidative wear to be discharged. Under the relative displacement caused by the cyclic alternating load, these oxidation products act as abrasive particles together with the wear debris generated by the adhesive wear and the foreign abrasives (dust, impurity particles contained in the lubricating oil, etc.) that fall into the connecting parts. During the rotation and sliding process of the auxiliary part, it moves on the surface of the key teeth of the inner and outer spline couplings to participate in frictional contact, causing the surface material of the spline coupling to fall off, thereby forming three-body abrasive wear.

(3) Landing state

When the aircraft is landing, it is subjected to irregular frequency impact loads; abrasive wear is very serious and is accompanied by slight adhesive wear, fretting wear, and oxidation wear, which continue to accelerate the wear of spline teeth. This is the wear mechanism of the aircraft in one take-off and landing cycle.

As a result of the accumulation of early wear, the involute spline without a centering surface will be worn out earlier than the fixed load cycle under a certain number of load cycles. The clearance of the tooth side of the spline on the heart surface is increased, the vibration effect is strengthened, and the deformation of the tail shaft causes the spline to slide relative to the tail surface, and its wear becomes more and more severe and eventually fails. However, the spline with a centering surface improves the spline misalignment to a certain extent, and when the spline without a centering surface wears to a certain degree in the early stage, the spline with a centering surface wears well. The center surface is important, but after accumulation of wear in the later period, the centering surface is worn out, the positioning gap increases, and the increase in the positioning gap makes the working condition of the spline with the centering surface worse than that of the spline without the centering surface. The misalignment condition is more serious, so after a certain number of wear cycles, the spline with a centering surface will wear out quickly under the coupling effect of misalignment, tail shaft deformation, and external input alternating load.

The material of the aviation floating involute spline couplings is alloy steel 40CrNiMoA, and its chemical composition (wt%) is shown in Table 1.

| Table 1. Chemical composition of alloy steel 40CrNiMoA (wt%). |
|----------------|---------|---------|---------|---------|---------|---------|---------|
| C   | Si     | Mn      | Mo      | Cr      | Ni      | Fe      |
| 0.38 | 0.18   | 0.65    | 0.2     | 0.7     | 1.45    | Rest    |
3. Floating Spline Coupling Wear Prediction Model

In recent years, the Archard adhesive wear calculation formula has generally been used for calculating the tooth surface wear of the spline coupling. Due to the traditional Archard calculation model being mainly based on the macroscopic wear situation, to make the Archard wear calculation formula more suitable for the actual wear of the involute spline coupling, scholars have conducted a lot of research. Ding et al. organized and analyzed the abrasive wear calculation formula and the Archard adhesive wear calculation model and introduced an Archard calculation model suitable for fretting wear, as shown in Equation (1):

\[ h(x) = 2k \cdot s \cdot p \]  \hspace{1cm} (1)

where \( k \) is the wear coefficient; \( s \) is the relative sliding distance of the spline coupling, in mm; and \( p \) is the contact pressure on the tooth surface of the spline coupling, in MPa.

Aiming at the special working environment of the aviation floating involute spline coupling, in order to make the above Equation (1) more suitable for calculating the tooth surface wear of the aviation floating involute spline coupling, this article focuses on the aviation involute spline; the specific force situation of the auxiliary tooth surface is analyzed. Taking the midpoint of the contact width of the single tooth surface of the spline coupling, the normal force of the tooth surface is simplified to the normal force \( F_n \) at the midpoint of the concentration, and \( F_n \) is decomposed at this midpoint. The tooth surface normal force \( F_n \) is decomposed into a circumferential component force \( F_t \) and a radial component force \( F_r \). At the end of the driven shaft in the external spline, the relative sliding speed of this node is the same as the circumferential component force of the normal force. The force distribution of a node on the tooth surface is shown in Figure 2 below.

![Figure 2. Analysis of the force on the tooth surface of the involute spline.](image)

For the aviation floating involute spline coupling in the working process, there is the relative slip distance in the axial direction and the relative slip distance in the radial direction, respectively. The plane coordinate system is established on the tooth surface of the node \( s_j \). During the simulation of the open-line spline coupling, every time a cycle is performed, the relative slip distance of this node in the two directions is expressed as \( s_{1j} \) and \( s_{2j} \), respectively, so after a cycle, the relative slip distance at this node is Equation (2). Because the existence of the axial floating distance will affect the axial relative slip distance at the spline coupling tooth surface node, the relative slip distance is expressed as \( s_{0j} \) at this time, and the calculation formula is Equation (3).

\[ s_j = \sqrt{s_{1j}^2 + s_{2j}^2} \]  \hspace{1cm} (2)

\[ s_{0j} = \sqrt{s_{1j}^2 + s_{2j}^2 + s_3^2} \]  \hspace{1cm} (3)
Aiming at the change of the involute slip distance of the above formula, the classic Archard formula of Equation (1) is optimized, and the calculation equation of the wear depth of the spline coupling in one cycle is shown in the following Equation (4); \( h(x)_j \) corresponds to the node in each where the wear depth under the cycle can realize a more accurate prediction of the wear depth of the tooth surface of the floating spline coupling.

\[
h(x)_j = 2k \cdot s_0j \cdot p \tag{4}
\]

As the spline coupling is in the working process, the tooth surface contact pressure of the spline tooth surface is constantly changing, and the relative sliding speed between the spline and the external spline is also constantly changing within a certain period of time. During the operation of the spline coupling, there are relative slip speeds in two directions at a certain node on the tooth surface of the spline coupling, as shown in Figure 3. Calculating the time derivative at both ends of the above Equations (2) and (3) to obtain the relative slip rate at the node, there is the relative slip velocity \( v_1 \) in the axial direction and the relative slip \( v_2 \) in the radial direction, respectively. The figure is a schematic diagram of two relative slip speed directions at a certain node, and the direction indicated by the arrow is the positive direction, as shown in the following formula. After the relative slip speed is compounded, the relative slip speed of a certain point on the surface of the key tooth is as shown in Equations (5) and (6).

\[
v_j = \sqrt{v_{1j}^2 + v_{2j}^2} \tag{5}
\]

\[
v_{0j} = \sqrt{v_{1j}^2 + (v_{2j} + v_{3j})^2} \tag{6}
\]

![Figure 3. Speed synthesis of a certain point on the tooth surface of the spline coupling.](image)

During the operation of the spline coupling, with fretting wear, temperature rise, and other factors, the relative slip rate at the node will continue to change with time, and then the above equation is used to derive the event and integrate it on both sides, as shown in the following Equations (7) and (8); as shown, the optimized Archard wear calculation formula is obtained.

\[
\frac{dh(x)_j}{dt} = 2k \cdot \frac{ds_0j}{dt} \cdot p \tag{7}
\]

\[
h(x)_j = 2k \int_{t_1}^{t_2} (v_{0j} \cdot p)dt \tag{8}
\]

In the formula, \( v_{0j}(t) \) and \( p(t) \) are the curves calculated by simulation, \( j \) is a point on the curve, the unit of \( v_{0j}(t) \) is \( \text{m/s} \), and the unit of \( p(t) \) is \( \text{pa} \).
The optimized Archard wear calculation model is combined with the finite element simulation calculation, and the modeling calculation of the aeronautical floating involute spline coupling under actual working conditions is carried out in the Abaqus software in order to obtain the tooth surface contact stress of the spline coupling and the relative slip rate simulation results. The contact stress and the relative slip rate at the tooth surface nodes of the spline coupling obtained by simulation change with time increments, and they are brought into the optimized Archard formula. The trapezoidal formula is defined by a definite integral to calculate the spline coupling’s certain node depth of wear. The definite integral trapezoidal formula is applied to the optimized Archard calculation model, and the wear calculation model suitable for aviation floating involute spline couplings is finally determined, as shown in the following Equations (9)–(11):

\[ A = f(\xi_1)\Delta x_1 + f(\xi_2)\Delta x_2 + f(\xi_3)\Delta x_3 + f(\xi_4)\Delta x_4 + \cdots + f(\xi_i)\Delta x_i \]  

\[ A = \lim_{\lambda \to 0} \sum_{i=1}^{n} f(\xi_i)\Delta x_i \]  

\[ h = 2K\lim_{\lambda \to 0} \sum_{i=1}^{n} v_{0j}(t_i)p(t_i)\Delta x_i \]

where \( A \) is the wear base area, mm\(^2\); \( K \) is a dimensionless unit; \( h \) is the wear depth, mm; \( \Delta x_i \) is the length of the microsegment, and the subscript is the \( i \)th microsegment; \( v_{0j}(t_i) \) is the speed of point \( j \) on the curve at time \( t \) of the \( i \)th segment; and \( p(t_i) \) is the stress at this point at time \( t \).

4. Influence of Different Working Conditions on the Wear of Spline Couplings

4.1. Establishing the Geometric Model of the Spline Coupling

The engineering design dimensions of the spline coupling are established in the finite element software, and the geometric model of the involute spline coupling is established. The basic design parameters of the involute spline coupling are shown in Table 2.

**Table 2. Basic design parameters of involute spline couplings.**

<table>
<thead>
<tr>
<th>Name</th>
<th>Parameter</th>
<th>Name</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of teeth ( z )</td>
<td>12</td>
<td>( a_1 ) (mm)</td>
<td>9</td>
</tr>
<tr>
<td>Module ( m ) (mm)</td>
<td>1.25</td>
<td>Torque ( T ) (Nm)</td>
<td>50</td>
</tr>
<tr>
<td>Speed ( r/\text{min} )</td>
<td>900</td>
<td>Poisson’s ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Internal spline shaft diameter ( D_0 ) (mm)</td>
<td>25</td>
<td>Friction factor ( \mu )</td>
<td>0.2</td>
</tr>
<tr>
<td>Inner hole diameter of the outer spline ( D_b ) (mm)</td>
<td>8</td>
<td>Elastic modulus ( E ) (GPa)</td>
<td>210</td>
</tr>
<tr>
<td>Compressive strength (MPa)</td>
<td>980</td>
<td>Yield strength (MPa)</td>
<td>835</td>
</tr>
</tbody>
</table>

To clearly analyze the force change of the floating involute spline during the simulation process, the external spline model was taken as an example. In the case of no load, the teeth were numbered as shown in Figure 4. The axial floating distance mentioned in this paper is changed by the degree of spline subtooth engagement; when the spline subtooth is fully engaged, then the axial floating distance at this time is 0 mm. When the spline subtooth is not fully engaged, the floating distance is generated in the axial direction. CSHEAR1 and CSHEAR2 refer to the shear stress on the contact surface of the spline subtooth; CSHEAR1 is the shear stress concentrated in the tip of the tooth and the root area, and CSHEAR2 is the shear stress concentrated in the middle of the tooth surface.
To clearly analyze the force change of the floating involute spline during the simulation process, the contact area of the internal spline in the dynamic simulation is shown in the red rectangle box in Figure 5b below.

4.2. Establishment of a Finite Element Model of Spline Coupling

4.2.1. Finite Element Model Settings

According to the geometric dimensions of the involute spline couplings shown in Table 2 above, based on the actual working condition structure in the aviation industry, it is easier to perform analysis in the simulation software Abaqus. The material property of the model is defined as linear elasticity, and the spline couplings created in the Abaqus software are shown in Figure 5a below. In the finite element simulation calculation, the model is divided into a finite number of regular hexahedral grid cells, which is conducive to the success of the simulation calculation and can improve the accuracy of the finite element simulation calculation. Since the tooth profile of the involute spline coupling is not a regular shape, manual meshing is used when meshing the model. Compared to automatic computer division, the finite element model manual sliding meshing method can effectively reduce the number of tetrahedral meshes and increase the number of hexahedral meshes, thus improving the accuracy of finite element simulation calculations. The grid type is set to C3D8R. The design constraints and loading conditions of the spline coupling model are shown in Figure 5a below to simulate actual working conditions. The contact area of the internal spline in the dynamic simulation is shown in the red rectangle box in Figure 5b below.

Figure 5. Finite element model of spline coupling: (a) dynamic simulation diagram of spline pair engagement and (b) dynamic simulation diagram of internal spline; the torque $T$ is 500 N/m, and the speed $N$ is 1500 r/min.

4.2.2. Working Conditions

According to the finite element model of aeronautical floating involute spline coupling established in Section 4.1 and the actual installation method of aeronautical floating involute spline coupling, three different types of constraints are set in the finite element analysis software with the floating distance of the spline coupling as a variable. From the above modeling of the aviation floating involute spline coupling, it can be seen that the external...
spline finite element model only releases the rotation and movement of the z-axis, and the z-axis movement of the external spline finite element model sets three constraints, as shown in Table 3.

Table 3. Working conditions of aviation floating involute spline coupling.

<table>
<thead>
<tr>
<th>Working Condition</th>
<th>Floating Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 mm</td>
</tr>
<tr>
<td>2</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>3</td>
<td>0.6 mm</td>
</tr>
</tbody>
</table>

When setting the constraint conditions, to achieve the comparison of the simulation results, the floating distance is set as 0.3 mm and 0.6 mm. In the simulation process, the internal spline only releases the rotation of the z-axis. The external spline not only releases the rotation of the z-axis but also allows movement along the z-axis. To simulate the constraint of aviation floating involute spline couplings under ideal conditions, the inner and outer splines are assembled to ensure the coincidence of the axes of the inner and outer splines during the assembly process, the floating speed of the aviation floating involute splines is explored. When the floating distance affects the depth of wear of the tooth surface of the spline coupling, the influence of factors such as axis offset and axis deflection can be prevented.

4.3. Distribution Law of Wear Depth of the Spline Coupling Tooth Surface

4.3.1. Constraint 1, Distribution Law of the Depth of Wear along the Axial Direction at Different Positions of Tooth Height

When the floating distance is 0 mm, the transient process of the actual spline coupling is simulated to obtain the contact stress cloud diagram of the spline coupling tooth surface, as shown in Figure 6. When the floating distance is 0 mm, the model is built with a tolerance level of 6, and the tooth flank clearance is randomly distributed; there is a certain difference in the contact stress distribution between the teeth, but the overall contact between the teeth can be obtained. The stress distribution is basically the same. The contact stress distribution on each tooth surface is analyzed, and the contact stress distribution of the tooth surface is relatively uniform along the axial direction. Along the direction of tooth height, the contact stress is the largest at the edge of the tooth tip, and downward along the direction of tooth height, the contact force of the tooth surface becomes smaller, and the stress at the rear tooth gradually increases, approaching the edge where the inner spline and the outer spline are in contact with the tooth surface. The contact stress value is larger at the time, and then the contact stress becomes smaller. Because the involute does not touch the bottom of the spline tooth, the contact stress is 0 mm. Constraint 1, i.e., the simulation work situation, is ideal, so each tooth’s overall contact stress distribution is roughly the same.

Figure 6. The contact stress cloud of the tooth surface when the floating distance is 0 mm (MPa).
The contact stress is explored at a certain point on the tooth surface of the spline coupling. The shear stress cloud and the CSHEAR1 stress cloud images from the simulation are shown in Figure 7a, and the CSHEAR2 stress cloud image from the simulation is shown in Figure 7b. It can be seen from Figure 7a that the shear stress distribution of CSHEAR1 is mainly concentrated in the tooth tip and tooth root. The stress in the middle area is relatively small. The shear stress of each tooth is evenly distributed, and there is no obvious stress concentration. The cloud diagram of the shear stress distribution in the CSHEAR2 direction is shown in Figure 7b. The stress distribution is concentrated mainly on both sides of the surface of the spline ring of the tooth. Most teeth do not have an obvious stress concentration. Due to the existence of randomly distributed tooth flank clearance, individual teeth are right, there is a stress concentration on the side tooth tops, and the overall stress distribution in the CSHEAR2 direction of each tooth is relatively uniform.

![Figure 7. Cloud diagram of shear stress distribution when the floating distance is 0 mm (MPa):](image)

(a) stress cloud diagram of CSHEAR1; (b) stress cloud diagram of CSHEAR2.

The relative slip rate distribution cloud diagram when the floating distance is 0 mm is shown in Figure 8. The relative slip rate distribution cloud diagram of the spline coupling tooth surface is similar to the spline coupling tooth surface contact stress contact cloud diagram, and the tooth top position is along the axis. There is an area where the relative slip rate is relatively large and then gradually decreases along the tooth height direction. The relative slip rate is the highest at the position where the spline coupling contacts the tooth root, which is the same as the contact stress distribution on the tooth surface of the spline coupling. The relative slip rate of the positions on both sides is 0 mm/s. The reason for this phenomenon is that only the inner side unit of the spline coupling has an effect on this unit, which causes the relative slip rate of the units at both ends of the spline coupling tooth surface to be 0 mm. The relative slip rate distribution of each tooth is analyzed, and the relative slip rate of each tooth is evenly distributed when the floating distance is 0 mm.

![Figure 8. Cloud diagram of relative slip rate distribution when the floating distance is 0 mm (MPa).](image)

After extracting the contact stress and relative slip speed data from the tooth surface contact data from the simulation results and bringing them into the above-optimized wear calculation model, the wear depth distribution curve at different tooth height positions and different axial positions of the spline teeth is obtained, as shown in Figure 9a,b. It can be seen that when the floating distance is 0 mm, the tooth surface wear depth of the spline coupling is relatively uniform in Figure 9a. At 0 mm, the relative slip speed simulation data are 0 mm/s, and the wear depth is 0 mm. For the integrated spline coupling at the
axial position of 2 mm-9 mm, the spline coupling wears uniformly along the axial direction, and the wear of the top position of the tooth is more serious than that of the position of the tooth root. The wear depth distribution curve at different axial positions shows that the tooth surface wear distribution at different axial positions is basically the same in Figure 9b. Wear is more severe in the radial position of the spline at 0 mm. Wear is the most serious in the 2.5 mm position. The wear depth is 0 mm in the 3–4 mm radial position because the inner and outer spline teeth are not in contact with each other. The comprehensive analysis shows that the wear depth distribution is similar to the tooth surface’s wear distribution.

Figure 9. Wear depth distribution when the floating distance is 0 mm: (a) wear depth distribution at different tooth height positions; (b) wear depth distribution at different axial positions.

4.3.2. Constraint 2, Distribution Law of Wear Depth along the Axial Direction at Different Tooth Height Positions

1. Stress analysis of contacts

The dynamic simulation result of the contact stress of the spline coupling under constraint 1 in Figure 10 shows that the internal spline and the external spline only float in the axial direction. The contact distribution of each tooth of the spline coupling should be basically the same. The force of each tooth of the spline coupling is relatively uniform.

Figure 10. Cloud diagram of the contact stress distribution of the tooth surface with a floating distance of 0.3 mm (MPa).

Taking tooth 1 as an example, the contact stress distribution on the tooth surface of the spline is analyzed, and the following rules are obtained: Along the radial direction of the spline tooth, the contact stress in the tooth tip area of the spline coupling is larger, and the contact stress in the middle area of the spline coupling gradually becomes smaller along the tooth root direction. From the middle area to the lower part of the contact area of the spline coupling, the contact stress gradually becomes larger. There is no contact at the root of the spline when the spline coupling is running, so the contact stress is 0 MPa. Along the axial direction of the spline teeth, the spline coupling has an axial floating speed of 0.3 mm/s and a displacement of 0.3 mm along the axial direction. There is obvious uneven
stress distribution at the right end of the spline tooth axis. The contact stress at both ends of the top area along the axial direction is greater, and the contact stress between the two ends and the middle area of the spline coupling tooth root area along the axial direction is greater. There is a gradual decrease and then a gradual increase. Due to the axial floating of the spline coupling, the change in contact area at the right end of the external spline is affected. The contact stress varies greatly at the right end of the spline shaft. At the right end of the tooth root and the middle area of the tooth surface, the contact stress decreases rapidly, and the contact stress at the right end is basically 0 MPa.

2. Relative slip rate analysis

The cut stress cloud diagram with a floating distance of 0.3 mm is shown in Figure 11a,b. The shear stress cloud diagram in the direction of CSHEAR1 is shown in Figure 11a. It can be seen from the figure that due to the existence of the floating distance, the spline coupling tooth surface CSHEAR1 shears, and the shear stress concentration is significant. There is an obvious stress concentration at the top of the spline coupling, and the shear stress is the largest at the top of the tooth. The stress value gradually decreases along the tooth height, and the stress value gradually increases at the bottom of the tooth. There are certain differences in the shear stress of CSHEAR1 on the tooth surfaces of different spline couplings, mainly due to the existence of random clearance. Similar to the contact stress distribution mentioned above, the shear stress of CSHEAR1 is greater on the left side of the shaft end, and the shear stress on the right side of the shaft end is 0 MPa. In the direction of CSHEAR2, as shown in Figure 11b, the shear stress is mainly concentrated at the top of the tooth and the left side of the tooth surface, and the shear stress value on the right side of the tooth surface is basically 0 MPa.

The result of the dynamic simulation of the relative slip rate of the spline coupling under constraint 2 is shown in Figure 12. It can be concluded from the figure that the relative slippage of each tooth of the spline coupling is due to the existence of the axial floating phenomenon of the external spline. There is an uneven distribution of the rate of movement. The relative slip distribution of each spline tooth is basically the same. The relative slip rate of the tooth surface of the spline coupling is mainly distributed in the tooth root and in the middle area of the tooth surface. The relative slip rate of the tooth surface of the spline coupling is the largest at the left end of the spline coupling, and the relative slip rate gradually decreases along the axial direction and then becomes larger at the right end of the spline coupling. Due to the existence of axial floating, the rightmost end of the outer spline is relatively slippery, the distribution of the transfer rate is uneven, and the relative slip rate at the right end is basically 0 mm/s. The main reason is that due to axial float, the contact time between the rightmost tooth surface of the outer spline and the inner spline is relatively short. Because the spline coupling model of each tooth in the spline coupling has an assembly level of H6/h6, there is a certain gap between the inner and outer spline couplings, which leads to the relative slip rate and the contact stress distribution of each inner spline tooth surface. They are not the same, and there is a certain difference in the relative slip rate of each tooth.
when the floating distance is 0.6 mm. It can be seen from Figure 14 that the contact stress
wear depth distribution at different axial positions is shown in Figure 13b; when there is
when the floating distance is 0.3 mm, as shown in Figure 13a, b. The depth of wear at the
root of the surface of the tooth is relatively stable. According to the curve in Figure 13a, at
the tooth height of 5 mm and the tooth height of 7 mm, it can be seen that when there is a
floating distance of 0.3 mm, the wear depth of the tooth surface tends to become larger and
larger along the axial direction. The left end of the spline tooth surface is 0 mm–2 mm, and
the wear depth is large. Comparative analysis shows that the wear depth at the left end of
the spline from 0 mm to 6 mm is less than that of the 0 mm floating distance, and the wear
depth at the right end of the spline from 6 mm to 9 mm is greater than that of the 0 mm
floating distance. The general analysis shows that when the floating distance is 0.3 mm,
the wear depth of the spline tooth surface is unevenly distributed along the axial direction,
which will cause the occurrence of misalignment of the inner and outer spline shaft axes,
which will further increase the wear of the worn spline coupling tooth surface. severe. The
wear depth distribution at different axial positions is shown in Figure 13b; when there is a
floating distance of 0.3 mm, the wear depth along the radial distribution curve of the
surface of the spline tooth is basically the same as when there is no floating distance.

The relative slip velocity distribution of the tooth surface with a floating distance of
0.3 mm (MPa).

The simulation result data of the spline coupling are extracted to obtain the wear
depth distribution curve at different tooth height positions and different axial positions
when the floating distance is 0.3 mm, as shown in Figure 13a, b. The depth of wear at the
root of the surface of the tooth is relatively stable. According to the curve in Figure 13a, at
the tooth height of 5 mm and the tooth height of 7 mm, it can be seen that when there is a
floating distance of 0.3 mm, the wear depth of the tooth surface tends to become larger and
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which will further increase the wear of the worn spline coupling tooth surface. severe. The
wear depth distribution at different axial positions is shown in Figure 13b; when there is a
floating distance of 0.3 mm, the wear depth along the radial distribution curve of the
surface of the spline tooth is basically the same as when there is no floating distance.

Figure 12. The relative slip velocity distribution of the tooth surface with a floating distance of
0.3 mm (MPa).

Figure 13. Wear depth distribution at a floating distance of 0.3 mm: (a) wear depth distribution at
different tooth height positions; (b) wear depth distribution at different axial positions.

4.3.3. Constraint 3

Figure 14 is a cloud diagram of the contact stress distribution of each tooth surface
when the floating distance is 0.6 mm. It can be seen from Figure 14 that the contact stress
distribution of each tooth surface is uneven at the top and root of some tooth surfaces.
There is an obvious stress concentration phenomenon. The maximum contact stress to the
tooth surface reaches 9608 MPa, resulting in serious deformation of the spline coupling.
The main reason is that when the floating distance is 0.6 mm, the contact length of the
tooth surface of the inner and outer spline teeth is reduced, making the contact stress of the
The maximum contact stress of the tooth surface at this time is 5 times the maximum contact stress of the floating distance of 0 mm. It can be seen that when the floating distance of the spline coupling reaches a certain value, the contact stress of the tooth surface increases suddenly, which makes the spline coupling seriously deformed and not able to meet the normal use requirements.

![Contact Stress Cloud Diagram](image1)

**Figure 14.** The cloud diagram of the contact stress distribution of the tooth surface with a floating distance of 0.6 mm (MPa): (a) cloud diagram of the contact stress distribution on the tooth surfaces of teeth 1, 2, and 3; (b) cloud diagram of the contact stress distribution on the tooth surfaces of teeth 4, 5, and 6; (c) cloud diagram of the contact stress distribution on the tooth surfaces of teeth 7, 8, and 9; (d) cloud diagram of the contact stress distribution on the tooth surfaces of teeth 10, 11, and 12.

The shear stress distribution cloud diagram of the spline coupling tooth surface with a floating distance of 0.6 mm is shown in Figure 15. From Figure 15a,b, the shear stress cloud diagram in the direction of CSHEAR1 can be obtained. Due to the severe deformation of the surface of the spline coupling tooth, CSHEAR1 directional shear stress is small, and there is no obvious stress concentration position overall. Analysis of Figure 15c,d showing the CSHEAR2 direction shear stress cloud chart shows that when there is a floating distance of 0.6 mm, the shear stress in the CSHEAR2 direction has an obvious stress phenomenon in individual teeth, and the distribution of each tooth is quite different.

![Shear Stress Cloud Diagram](image2)

**Figure 15.** Shear stress distribution cloud diagram with a floating distance of 0.6 mm: (MPa): (a,b) CSHEAR1 direction shear stress cloud diagram; (c,d) CSHEAR2 direction shear stress cloud diagram.
The cloud diagram of the relative slip velocity distribution of each tooth surface with a floating distance of 0.6 mm is shown in Figure 16a,b. Due to the serious deformation of the tooth surface of the spline pair, the relative slip speed of each tooth surface is basically 0; there is a certain relative slip speed at the root of the individual tooth, and the wear depth of most tooth surfaces is basically 0 mm. The spline pair is seriously deformed and cannot meet the use requirements.

Figure 16. Relative slip velocity distribution of the tooth surface with a floating distance of 0.6 mm (MPa): (a) the distribution diagram of the relative sliding velocity of the lower tooth surface of teeth 1–6; (b) the distribution diagram of the relative sliding velocity of the lower tooth surface of teeth 7–12.

Through the analysis of stress and wear for the axial floating distances of 0 mm, 0.3 mm, and 0.6 mm, it was found that when the floating distance gradually increases, the depth of axial flaring wear increases along the axial direction, and the increase rate is most obvious at 0.3 mm; when the floating distance is 0.6 mm, the tooth surface of the spline is seriously deformed, the stress is concentrated, the work cannot be performed, and involute spline coupling is invalidated.

5. Analysis of Actual Aviation Floating Involute Wear
5.1. Invalid Parts of Aviation Floating Involute Spline Coupling

Figure 17 shows the wear of the spline shaft in the transmission system of an aviation helicopter. A floating installation method is adopted for the spline shaft during assembly. This installation method can effectively reduce the external load on the spline shaft. The effect of stress can effectively reduce the expansion of the spline shaft caused by heat and other factors during the operation of the spline shaft. However, with the relative axial floating of the inner and outer spline shafts, the wear on the tooth surfaces of the spline coupling increases. If the spline shaft in the transmission system of the aviation helicopter is removed, as shown in Figure 18, it can be seen that the inner spline tooth surface forms a stepped wear mark after the tooth surface is worn, and the outer spline repeatedly moves in the axial direction in the inner spline hole, causing severe wear of the spline and thus failing to meet the requirements of use. The working time of this failed part is 1000 h, and the allowable floating amount during assembly is 0.3 mm. The other working conditions are basically the same as the setting conditions of the aviation floating involute spline coupling simulated. The observation of the wear depth of the wear failure parts realizes the verification of the theoretical research on the wear depth of the aviation floating involute spline coupling in this work.

Figure 17. Wear of floating involute spline coupling in an aerospace transmission system: (a) red-marked worn internal splines and (b) red-marked worn external splines.
5.2. Observation of the Surface of the Splint of the Tooth

To facilitate the effective observation of the tooth surface of the inner spline, this shaft is processed by wire cutting, and each spline after the cut is placed under the Olympus digital microscope for observation. After the spline tooth surface wear profile is obtained, the 3D scanning function of this microscope is used to observe the tooth surface wear depth to obtain the tooth surface wear depth value. Figure 19 below shows the Olympus DSX510 digital microscope.

5.3. Observation Results and Analysis

The wear morphology of each tooth surface is observed, as shown in Figure 20 below.

In Figure 20, a wear diagram is shown for each tooth surface of teeth 1–12, from which it can be seen that the tooth surface is severely worn. What can be seen at the upper end of the spline tooth is that the worn tooth surface forms a steplike drop from the worn tooth surface; at the lower end of the spline tooth in the figure, the inner and outer spline subsets float axially along the inner spline tooth downward in the figure, causing the spline tooth surface here to be completely worn. Further measurement of the wear depth of the tooth surface along the axial direction at different tooth height positions is performed, as shown in Figure 21; the red line in the figure represents the measured position along the axial direction, and the maximum difference between the unworn and worn places at the location of the red line is the wear depth value of the tooth surface.
Figure 19. Olympus DSX510 digital microscope.

5.3. Observation Results and Analysis

The wear morphology of each tooth surface is observed, as shown in Figure 20 below.

Figure 20. High-definition photos of spline teeth after wear.

In Figure 20, a wear diagram is shown for each tooth surface of teeth 1–12, from which it can be seen that the tooth surface is severely worn. What can be seen at the upper end of the spline tooth is that the worn tooth surface forms a steplike drop from the worn tooth surface; at the lower end of the spline tooth in the figure, the inner and outer spline subsets float axially along the inner spline tooth downward in the figure, causing the spline tooth surface here to be completely worn. Further measurement of the wear depth of the tooth surface along the axial direction at different tooth height positions is performed, as shown in Figure 21; the red line in the figure represents the measured position along the axial direction, and the maximum difference between the unworn and worn places at the location of the red line is the wear depth value of the tooth surface.

Figure 21. Measurement of the wear depth of the surface of the spline tooth: (a) wear depth map of tooth 1; (b) wear depth map of tooth 5; (c) wear depth map of tooth 9.

According to the method in Figure 21 above, the wear depth on each tooth is measured to obtain the maximum wear depth of each tooth. The results are shown in Table 4.

Table 4. Actual wear depth and theoretical wear depth for each tooth.

<table>
<thead>
<tr>
<th>Tooth Number</th>
<th>Actual Wear Depth (µm)</th>
<th>Theoretical Wear Depth (µm)</th>
<th>Error Value (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>467.9</td>
<td>441.3</td>
<td>26.2</td>
</tr>
<tr>
<td>2</td>
<td>476.9</td>
<td>449.9</td>
<td>27.0</td>
</tr>
<tr>
<td>3</td>
<td>456.8</td>
<td>482.4</td>
<td>23.8</td>
</tr>
<tr>
<td>4</td>
<td>466.0</td>
<td>439.9</td>
<td>26.1</td>
</tr>
<tr>
<td>5</td>
<td>492.5</td>
<td>430.6</td>
<td>61.9</td>
</tr>
<tr>
<td>6</td>
<td>483.8</td>
<td>428.3</td>
<td>55.5</td>
</tr>
<tr>
<td>7</td>
<td>543.6</td>
<td>521.3</td>
<td>22.3</td>
</tr>
<tr>
<td>8</td>
<td>482.5</td>
<td>453.1</td>
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</tr>
<tr>
<td>9</td>
<td>444.3</td>
<td>460.4</td>
<td>16.1</td>
</tr>
<tr>
<td>10</td>
<td>422.2</td>
<td>463.4</td>
<td>41.2</td>
</tr>
<tr>
<td>11</td>
<td>492.5</td>
<td>534.3</td>
<td>41.8</td>
</tr>
<tr>
<td>12</td>
<td>481.1</td>
<td>421.6</td>
<td>59.5</td>
</tr>
</tbody>
</table>

According to the wear gradient of the spline tooth surface, the average maximum wear depth of the spline tooth surface is 476.1 µm. Using the optimized wear theory model proposed in this article, the wear result of the pair of splines is 443.9 µm, and the error of the maximum wear depth of the actual surface of the spline tooth is 6.8%. Therefore, it is feasible to use the proposed optimized wear theory model combined with the finite element method to predict the wear of the flying involute spline.

6. Conclusions

This study observed the tooth surface of the existing aviation involute spline coupling and analyzed the wear mechanism of the tooth surface. Through the analysis of the force on the tooth surface of the aviation floating involute spline coupling, the traditional Archard wear theory model was optimized, and finite element software was used to simulate the aviation floating involute spline coupling under different floating distances. Finally, through the wear parts of aviation floating involute spline coupling, the wear depth of the tooth surface was measured with a digital microscope to realize the combination of the wear calculation model proposed and the finite element method to calculate the aviation floating involute spline coupling. The results of the study are as follows:
(1) The mechanism of wear of the tooth surface of the failed parts was analyzed and obtained. The main form of aeronautical floating involute spline wear was obtained; it is mainly abrasive wear, and the abrasive wear is very serious, accompanied by slight adhesive wear and fretting. Oxidative wear continues to accelerate the wear of spline teeth.

(2) In view of the axial movement of the aviation floating involute spline coupling, the axial movement speed is coupled with the relative slip rate caused by contact between the teeth to obtain a suitable model for calculating the wear of involute spline couplings.

(3) The actual working conditions of the aviation floating involute spline coupling are simulated. When the floating distance is 0.3 mm, the wear depth of the tooth surface changes significantly, and the wear depth increases along the floating end, which intensifies the damage to the spline coupling. When the wear depth reaches a certain value, the spline coupling is severely deformed and cannot meet the usage requirements.

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References
19. Ding, J.; Mccoll, I.; Leen, S. The application of fretting wear modelling to a spline coupling. Wear 2007, 262, 1205–1216. [CrossRef]