Study on Influence of Profile Modification on Transmission Performance of Spur Gear

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Abstract. Profile modification is an important method used for improving the spur gear transmission performance. By using the engineering software of Romax Designer, the transmission system model of single-stage cylindrical spur gear is established. And taking the elimination of impact loads in spur gear transmission process as the target, the full tooth profile modification of driving gear is completed with the modification curve of parabola. The flash temperature, oil film thickness and transmission error are taken as the indexes for measuring the transmission performance of spur gear. Through comparing the surface flash temperature, oil film thickness and transmission error before and after profile modification, the influence of profile modification on transmission performance of driving gear is obtained. The simulation and investigation results show that profile modification plays an important role in reducing the flash temperature, improving the tooth lubrication state and narrowing the fluctuation range of spur gear transmission error.

1. Introduction
During the actual operation of the involute spur gear pair, the tooth subjected to loading will occur elastic deformation, and normal pitch of the meshing teeth pair is not equal. Therefore, the interference and impact of mesh-in and mesh-out is generated [1-2]. This will cause the scraps on the tooth surface to accumulate near the pitch circle, and accelerate wear and agglutinate failure on tooth surface [3]. In addition, while the number of gear meshing teeth pairs is changing, the instantaneous impact load is also generated. In view of the above problems, the profile modification should be taken to alleviate the impact during gear meshing. Therefore, it is significance to study the influence of profile modification on the transmission performance of spur gear. In this paper, based on the numerical calculation of Romax Designer software, eliminating impact load is taken as the target of profile modification, the profile modification value of driving gear is obtained. Furthermore, through comparing the flash temperature, the oil film thickness and the transmission error before and after profile modification, the influence of profile modification on these three transmission performance indexes is analyzed. In order to provide reference for the studying on profile modification of spur gear.

2. Basic parameters of model used for simulation
The simulation model used for study is a single-stage cylindrical spur gear transmission system. The gear transmission system model established by Romax Designer is shown in Figure 1. (The box is not
considered in this model.) In Figure 1, \( n \) is the rev of the input shaft, which equal to 970 rpm; \( M \) is the load torque of output shaft, which equal to 886 N*m. In this simulation model, the material of gears is 40CrNiMo (steel brand of China), and the basic parameters of gear pair are shown in Table 1; The material of shafts is 45 carbon steel (steel brand of China); The bearings selected are all conical roller bearings of the type of SKF 31313; The lubricating mode of the gear transmission system is oil lubrication, and the oil brand is ISO VG 100 PAG Synthetic.

In addition, in order to make the simulation results easy to study, and avoid the influence of unbalanced load on the study of profile modification, the driving gear of the model has been axial modified by the method of helix angle modification. Therefore, the gear pair in this model has no unbalanced load [4].

### Table 1. Basic parameters of spur gear pair

|                  | The number of teeth | Modulus /mm | Tooth width /mm | Pressure angle /° |
|------------------|---------------------|-------------|-----------------|------------------|
| Driving gear     | 30                  | 3.0         | 78              | 20               |
| Driven gear      | 71                  | 3.0         | 78              | 20               |

3. **Determination of profile modification value**

3.1 **The theory and method of profile modification**

As shown in Figure 2 is the load distribution diagram of one tooth pair of spur gear in one meshing cycles. Before profile modification, the variation trend of the tooth load is polyline AMNHIOPD in whole meshing period. From the figure, \( \Delta q_1 \), \( \Delta q_2 \), and \( \Delta q_3 \) is the impact load of mesh in, the impact load of mesh out and the impact load during the number of gear meshing tooth pairs is changing, respectively. Sudden change of load can result in shock excitation. In order to avoid the adverse effect caused by the shocking load, the profile modification of the spur gear is required. And through profile modification, the variation trend of the tooth load can change from polyline AMNHIOPD to polyline ABNHPDP.

At present, there are many kinds of methods used for calculating profile modification value in the world. And different countries and enterprises generally adopt different methods of profile modification according to their actual experience. In order to have better manufacturability in the process of gear machining [5-6], the profile modification method of pinion (driving gear) is full tooth profile modification in this paper. The diagram of profile modification is shown in Figure 3, the \( C_\alpha \) is the value of profile modification by the modification curve of parabola [7].
3.2 Calculating the profile modification value

Follow the procedure shown in Figure 4, and input different values of full tooth profile modification of driving gear manually to software of Romax Designer, the target value profile modification value $C_a^*$ can be obtained. Finally, it is calculated that the target profile modification value is 14μm.

Per unit length loads of tooth before and after profile modification are shown in Figure 5(a) and Figure 5(b). (In both Figure 5(a) and Figure 5(b), the meaning of abscissa are roll angle, which is the expansion angle of the tooth profile along the base circle, and the same below.) The comparison shows, the load acting on the top and root of the tooth of driving gear decreases significantly after profile modification. Moreover, it eliminates the instantaneous impact load during the changing of the number of meshing tooth pair.
4. The influence of profile modification on transmission performance of spur gear

4.1 The influence of profile modification on flash temperature of tooth surface

4.1.1 The theory of calculating the flash temperature of tooth surface. Using the software of Romax Designer, based on the flash temperature method, the flash temperature of gear tooth surface before and after profile modification are calculated [8]. And the formula of this theory is

\[ \theta_{\text{max}} = 0.62 \mu \omega_b^{3/4} \left( \frac{1}{\rho_1} + \frac{1}{\rho_2} \right)^{3/4} \frac{V_{\rho_1} - V_{\rho_2}}{B_1 \sqrt{V_{\rho_1} + B_2 \sqrt{V_{\rho_2}}}} \]  

In formula (1), \( \theta_{\text{max}} \) is flash temperature, which the unit is °C; \( \mu \) is friction coefficient; \( \omega_b \) is normal force on unit tooth width, which the unit is N/mm; \( E_{\text{red}} \) is the synthetical elastic modulus of gear pair materials, which the unit is MPa; \( \rho_1 \) and \( \rho_2 \) are respectively the radius of curvature of driving gear and driven gear at the meshing point, which the unit are mm; \( v_{\rho_1} \) and \( v_{\rho_2} \) are the tangential velocities of meshing gears along the contact surface at the meshing point, which the unit are mm/s; \( B_1 \) and \( B_2 \) are the thermal contact coefficients of meshing gears.

4.1.2 Simulation and analysis of flash temperature of tooth surface. Through numerical calculation of Romax Designer, the flash temperature the driving gear tooth surface before and after tooth profile modification are obtained, as shown in Figure 6(a) and Figure 6(b). Comparing the flash temperature before and after the profile modification can be known, profile modification makes the maximum temperature location of the tooth surface move from the top and root to the location near the pitch line. Moreover, the maximum flash temperature of the tooth surface has been decreased after profile modification. Therefore, profile modification is conductive to avoid or alleviate the agglutination of tooth surfaces.

4.2 The influence of profile modification on oil film thickness of tooth surface

4.2.1 The theory of calculating the oil film thickness of tooth surface. Using the software of Romax Designer, based on the film thickness formula of Dowson-Higginson line contact elastohydrodynamic lubrication, the minimum oil film thicknesses of gear tooth surface before and after profile modification are calculated [9-10]. And the formula of this theory is

\[ h_{\text{min}} = \frac{2.65 \alpha^{0.54} (\eta U)^{0.7} R^{0.43}}{E^{0.03} W^{0.13}} \]  

In formula (2), \( h_{\text{min}} \) is the minimum oil film thickness, which the unit is μm; \( \alpha \) is viscosity coefficient of lubricating oil, which the unit is mm²/N; \( \eta_0 \) is dynamic viscosity of lubricating oil, which the unit is
\( (N\cdot s)/mm^2 \); \( E' \) is the synthetical elastic modulus of gear pair materials, which the unit is MPa; \( R \) is the equivalent radius of curvature of a gear pair at the meshing point, which the unit is mm; \( U \) is the entrainment velocity of lubricating oil of a gear pair at the meshing point, which the unit is m/s; \( W \) is the load on unit contact length, which the unit is N/mm.

![Flash Temperature Graph](image1)

**Figure 6.** The flash temperature of driving gear before and after profile modification

4.2.2 Simulation and analysis of oil film thickness of tooth surface. Through numerical calculation of Romax Designer, the minimum oil film thicknesses of the driving gear tooth surface before and after tooth profile modification are obtained, as shown in Figure 7(a) and Figure 7(b). Comparing the Figure 7(a) and Figure 7(b) can be known, because the load of the single teeth-meshing area is larger, the oil film thickness in this area has a downward trend compared with the double teeth-meshing area. In addition, compared with before profile modification, the overall trend of oil film thickness after modification is increasing. And during the transition from double teeth-meshing area to single teeth-meshing area, the instantaneous decrease of oil film thickness is not appeared. Therefore, profile modification is conductive to improve the lubrication state of tooth surface.

![Oil Film Thickness Graph](image2)

**Figure 7.** The oil film thickness of driving gear before and after profile modification

4.3 The influence of profile modification on transmission error of gear

4.3.1 The theory of calculating the transmission error of gear. In the actual working process of gear mechanism, the actual transmission ratio of the gear pair fluctuates in the vicinity of the theoretical value, due to the factors such as manufacturing error and elastic deformation. In this paper, the transmission error of gear is measured by the displacement error on meshing line [11], and its value is
\[ TE = r_{b_2} \theta'_{2} - r_{b_1} \theta_1 \]  

In formula (2), \( TE \) is the displacement error on meshing line, which the unit is μm; \( r_{b_1} \) and \( r_{b_2} \) are respectively the base circle radius of driving gear and driven gear, which the unit is mm; \( \theta_1 \) is the theoretical rotation angle of driving gear, which the unit is rad; \( \theta'_{2} \) is the actual rotation angle of driven gear, which the unit is rad.

4.3.2 Simulation and analysis of transmission error of gear. Through numerical calculation of Romax Designer, the transmission error of the driving gear before and after tooth profile modification are obtained, as shown in Figure 8(a) and Figure 8(b). Comparing with before profile modification, the increase of maximum transmission error is 6.52%, and increase of minimum transmission error is 59.3% after profile modification. However, fluctuation range of gear transmission error is reduced by 73%. Thus, the profile modification is conductive to reduce the fluctuation range gear transmission error, vibration and noise.

![Figure 8. The transmission error of driving gear before and after profile modification](image)

5. Conclusions
In this paper, using the engineering software of Romax Designer as the numerical computing tool, with the modification curve of parabola, the full tooth profile modification of driving gear of single-stage cylindrical spur gear transmission system is completed. Based on that, the influence of profile modification on the transmission performance of spur gear is simulated and analyzed. Comparing the flash temperature, the thickness of oil film and the transmission error of driving gear before and after profile modification, the results show that gear profile modification plays a positive role in reducing the flash temperature, improving the lubrication state and narrowing the fluctuation range of gear transmission error. That is, the profile modification of gear is conductive to improve gear transmission performance.

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