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Optimization and Optimization Design of Gear Modification for Vibration Reduction Based on Genetic Algorithm

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Abstract: In order to determine the gear modification parameters accurately, genetic algorithm was introduced to reduce the fluctuation of the gear transmission error, and the gear modification parameters were optimized with high precision. The results show that the gear modification parameters determined by this method are accurate and effective, can avoid the meshing impact, and can greatly reduce the dynamic transmission error fluctuation of the gear. Compared with the direct use of finite element method for gear modification optimization, the calculation time of this algorithm is reduced from 26.81 d to 2.24 h. Genetic algorithm is used to optimize the weights of the hidden layer and output layer of the radial basis neural network. Finally, genetic algorithm is used to rationally select the crossover probability and mutation probability to optimize the gear design. By analyzing the influence of each design variable on the error fluctuation of gear transmission, the optimal combination of design variables is obtained. Then the tooth surface of the gear pair is optimized twice, and the optimal modification optimization scheme is obtained. Finally, the gear contact analysis is used to verify and optimize the design of the two-stage helical gear reducer. The results show that the performance of this algorithm is better than the original genetic algorithm and the design efficiency is high.

Keywords: genetic algorithm; gear modification; meshing impact; modification optimization; vibration reduction optimization

1 INTRODUCTION

Correct and reasonable gear transmission design is very meaningful for the whole mechanical transmission, such as optimizing the volume design of the transmission gear, optimizing the weight design, optimizing the transmission of a certain parameter design and so on. Because of its high parallelism, robustness and adaptive ability, genetic algorithm can effectively reduce the amount of computation, save the cost and time, and solve the search rules to reflect the characteristics of intelligence, and can effectively solve this difficulty. Therefore, it is of great significance to promote the application of genetic algorithm optimization technology in the optimization design of gear transmission, save the design time of gear transmission optimization, and make the optimization parameters reach the optimal value.

It is very important to control vibration and noise for the gear to have the characteristics of high speed, heavy load, light weight and miniaturization. In order to reduce the vibration and noise in the process of gear transmission, the meshing process can be carried out smoothly. With the continuous increase of aero-engine spindle speed, the possibility of fatigue fracture caused by vibration of accessory transmission gear increases sharply, which seriously endangers the flight safety of aircraft. The influence has been studied extensively abroad [1-3]. In recent years, the impact of gears under sudden initial velocity loading has been studied [4, 5]. Although the above research has made qualitative analysis on the size of the modification amount and the selection of the modification part, it has not put forward a quantitative method to determine the gear modification parameters.

In this paper, the finite element method and genetic algorithm were comprehensively adopted to optimize the gear modification parameters with the aim of reducing the fluctuation of gear transmission error, a system analysis model was established, and the meshing performance of the gear system was analyzed. The tooth surface modification parameters were optimized by genetic algorithm, and the common two-stage standard helical gear was optimized by improved genetic algorithm. Finally, the correctness of the optimization results is verified by comparing the fluctuation value of the transmission error and the load of the tooth surface before and after the optimization. The first part of this paper is introduction, the second part is related work. The third part is research on optimization of gear modification and vibration reduction based on genetic algorithm, the fourth part is research on gear modification optimization based on genetic algorithm, the fifth part is simulation, and the sixth part is conclusion.

2 RELATED WORK

At present, the impact of gear under sudden initial velocity loading is studied [6]. The finite element method was used to calculate the deformation of the gear teeth at each meshing position, and the modification amount was determined to be the deformation amount at the alternating meshing point of the gear teeth [7]. The amount of tooth profile modification under different loads was optimized by minimizing the transmission error excitation during gear meshing [8]. Static transfer error is taken as the optimization target of vibration and noise reduction, and genetic algorithm is used to determine the gear modification amount based on finite element method. It is found that it is necessary to manually adjust different meshing positions for several times to carry out finite element calculation [9, 10], and the time-varying stiffness incentive function corresponding to a certain tooth profile modification parameter (such as modification length and modification amount) can be fitted through the calculation results of multiple position points. However, different tooth profile modification parameters correspond to all the solving processes of stiffness incentive as described above. In order to solve this problem of large and complicated calculation, the agent model is used to optimize [11, 12], which is a common solution and method in current engineering. For gear modification optimization, the time-varying meshing stiffness is generally expressed by the first-order component of the Fourier transform function, and parameters such as meshing stiffness, exciting frequency and phase Angle need to be determined. In order to establish the time-varying meshing stiffness function of gears, the conventional single response function (such as polynomial response surface, spline curve, etc.) is difficult to meet the requirements of gear modification optimization [13, 14].

Researchers have carried out in-depth research on the optimization design of gear transmission. For example, in some small Spaces, the gear transmission is limited by the installation space, such as in the lunar vehicle, the size of the transmission device is limited to a small range [15], which requires us to optimize the design according to the minimum sum of central moments. Since the genetic algorithm is not limited by the nature of the problem itself, the form of optimization criteria, the form of model structure, the number of optimized parameters, etc., it only uses the objective function to carry out parallel global adaptive automatic search under the guidance of probability criteria [16], and it can deal with complex problems that are difficult to be solved by traditional optimization methods [17, 18]. By simulating the stress conditions of the prototype gear pair and the modified gear pair under loading conditions, the contact strength and root bending strength stress distribution diagram of the modified gear teeth can be effectively obtained, and the results can be compared with the contact stress diagram of the original gear, thus verifying the tooth profile modification theory and accurately determining the range of the modified amount [19, 20]. This method has a certain reference value in solving the convex contour modification quantity in this paper. Transmission error fluctuation of the mechanism under different modification amounts and their distribution, modification curves and modification lengths [21] were compared. In the traditional empirical design method (linear optimization method), discrete standard values such as modulus and number of teeth are treated as continuous variables, and then selected as standard values after optimization, which cannot guarantee the optimality of the results. With the development of optimization technology, the calculation results show that the algorithm has high computational efficiency [22] and is an effective optimization algorithm under complex constraints with multiple parameters. Artificial neural network was applied to optimize the gear design [23]. When MATLAB algorithm solves optimization design problems [24], although the program design is relatively simple, the standard value is treated as continuous variable in optimization [25].

Gear transmission system can be controlled by setting reasonable gear structure parameters, improving gear machining accuracy, improving gear structure type and micro-adjusting gear shape. It is not feasible to only change the gear material and gear structure to control the noise. The gear pair must have transmission errors in the meshing process, so it is not an ideal choice to invest a lot of money in the research and development of gear materials to obtain a small noise reduction effect. Micro modification of gear shape is often used to reduce the deformation caused by the pitch error and external load [26], in which the optimization variables include modulus, helix Angle, tooth width, tip clearance coefficient, etc. [27, 28]. The gear profile was changed by using two-factor and multi-level isometric modification method. The results show that the optimum parameters can make the contact stress evenly distributed and prolong the service life of the gear. A new parabolic modified bevel gear design method was proposed [29, 30]. It was found that under the same load, parabolic modification could reduce the maximum contact force and root stress of the bevel gear, reduce the peak value of transmission error, and change the contact mode from wave shape to parallelogram [31, 32]. According to the literature review, the relationship between gear modification parameter combination and system performance is not simple linear, and the corresponding relationship between them cannot be expressed by specific functional formulas. The traditional empirical formula has the defect of low accuracy in calculating the gear modification parameters; by using computer finite element analysis and intelligent optimization algorithm to solve the simulation experiment. However, many existing studies take meshing impact force, meshing stiffness, transmission error and other vibration excitation sources as optimization objectives, and rarely take the dynamic response performance of the system such as vibration acceleration as optimization objectives. It has become increasingly difficult to estimate gear vibration noise based on transmission error. Reducing the peak value of transmission error or improving the load distribution on the tooth surface may not achieve vibration and noise reduction of the transmission system. The special is in the high frequency band.

3 RESEARCH ON OPTIMIZATION OF GEAR MODIFICATION AND VIBRATION REDUCTION BASED ON GENETIC ALGORITHM

3.1 Research on Genetic Optimization Framework Design of Gear Modified Vibration Reduction

The actual meshing base of the gear deviates, and the meshing interference occurs when the gear teeth are in and out, which affects the smoothness of the gear drive. It is to repair a part of the interference part generated by the secondary tooth tip of a pair of meshing gear. The other is the root modification, that is, the interference part of the secondary root of a pair of meshing gears is repaired.

Table 1 Gear parameters

Name	Driving wheel	Driven wheel
Module	4 mm	4 mm
Number of teeth	28	28
Pressure Angle	22	22
Tooth width /mm	24	24
Speed n / r/min	3500	3500
Torque T / N·mm	50500	50500
Addendum height factor h	1	
Poisson's ratio of c	0.4	
Elastic modulus E / GPa	208	
Contact ratio λ	1.5543	

Tooth profile modification usually has the following methods. One is to trim the top and root of the pinion, while the matching big gear is not trimmed. The other is to repair the top of the tooth on the small and large gears, and to repair the top and root of the small and large gears individually. In this paper, a straight line trimming scheme is adopted for all the big and small gears. Taking a pair of spur gears as an example, gear parameters are shown in Tab. 1.

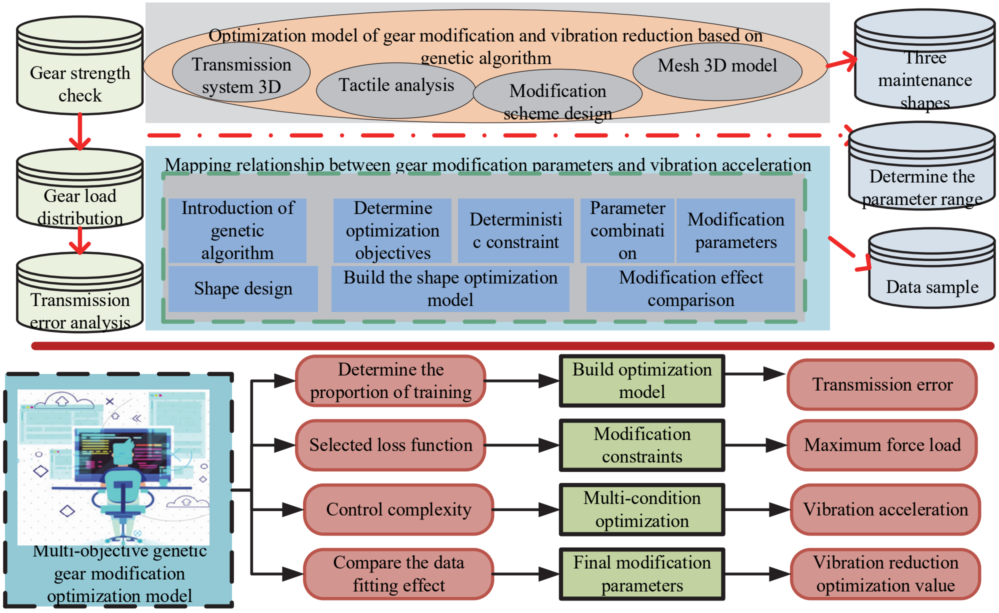

Figure 1 Genetic optimization framework for gear modification vibration reduction

Fig. 1 shows the genetic optimization framework for gear modification vibration reduction.

The variable scale is shown in Tab. 2.

Table 2 Variable scale

Variable	Meaning
r_b	base circle radius
e	gear transmission error
o_i	the sum of the modification amount of the gear pair
Δe	objective function
χ	deformation of the gear
k	tooth stiffness

3.2 Gear Modification Optimization Based on Genetic Algorithm

In the process of gear meshing, when the driving wheel turns r_1, the theoretical Angle of the driving wheel is r_2. However, due to the elastic deformation of the gear teeth and the instant impact of meshing, the Angle of the driving wheel is r_3. The vibration of the gear can be easily described by the Angle difference of the driven wheel, also known as the dynamic transmission error of the gear, expressed in the Angle form as:

$$r_A = \theta_i^{'} - \theta_i \tag{1}$$

r_a can be converted to the displacement on the line of engagement, expressed as e. If the base circle radius of the driven wheel is r_b, then:

$$e = r_A \times r_b \tag{2}$$

The goal of modification is to control the variation of gear transmission error e in a minimum range. The maximum value of the error is $e_{\max}$, and the fluctuation of the transfer error from any meshing point position l to the maximum meshing point is:

$$\Delta e = e_{\max} - e_i \tag{3}$$

It is stipulated that the normal pitch increase is positive. If the gear teeth are modified, the sum of the modification amount of the gear pair at the meshing point i is o_i, and the comprehensive deformation value of the meshing tooth pair at the meshing point is t, then:

$$\begin{aligned} e_i &= o_i - t \\ \Delta e &= e_{\max} - (o_i - t) \end{aligned} \tag{4}$$

It shows that at any meshing point, when the difference between the sum of the tooth modification o_i at the point and the comprehensive deformation mother of the point is closer to the maximum transfer error, the vibration of the gear will be smaller. When a set of modification parameters is determined, o_i determines that if ∆e is taken as the objective function, there must be a set of matching modification parameters that minimize ∆e. The angular displacement of the gear meshing point is converted to the displacement on the meshing line, and the meshing stiffness of the gear is calculated as follows:

$$K = \frac{\Delta e}{\chi} = \frac{\Delta e}{r_b} \times \frac{\theta}{r_b} \tag{5}$$

where χ is the deformation of the gear in the direction of the theoretical line of engagement.

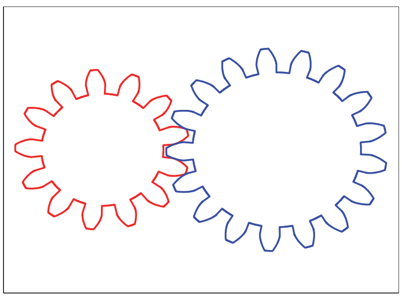
Figure 2 Finite element model of gear

According to the method mentioned above, 10 points were extracted within the meshing period of the gear respectively, and the tooth stiffness k was calculated using ANSYS finite element method. The finite element model is shown in Fig. 2.

The optimization objective selected is the minimum fluctuation value of gear transmission error, and the expression is as follows:

$$\min(\Delta RE) = \min(\max(\Delta RE) - \min(\Delta RE)) \tag{6}$$

where, ΔRE is the transmission error fluctuation value.

Therefore, the value range of each optimization design variable of the main and slave wheels of the output stage is preliminarily selected: the range of tooth tip trimming amount, drum shape amount and tooth end trimming amount is 0 - 30um. Screw correction –30 to 30 um; The initial trim angles of the main and driven wheels are 27.192 to 42.192 and 21.455 to 25.455, respectively. The starting position of the tooth end correction of the main and driven wheels is 0 - 15 mm, 77 - 95 mm, 0 - 9.5 mm, 73 - 85 mm. Fig. 3a shows the transmission error fluctuation corresponding to the correction starting position of different tooth ends. When the transmission error fluctuation value is small, the corresponding correction starting position of the tooth end ranges from 88 - 90 mm. Fig. 3b shows the transmission error fluctuation value corresponding to different gear tip trimming amounts. When the transmission error fluctuation value is small, the variation range of gear tip trimming amounts is 21 - 28 um.

The optimal design variable combination determined is the amount of top trimming edge, the starting Angle e of top trimming edge, the drum shape amount C, and the helix correction amount Ch, as shown in Tab. 3. After the second optimization, the optimal modification optimization scheme of the main and driven gears is obtained, as shown in Tab. 4.

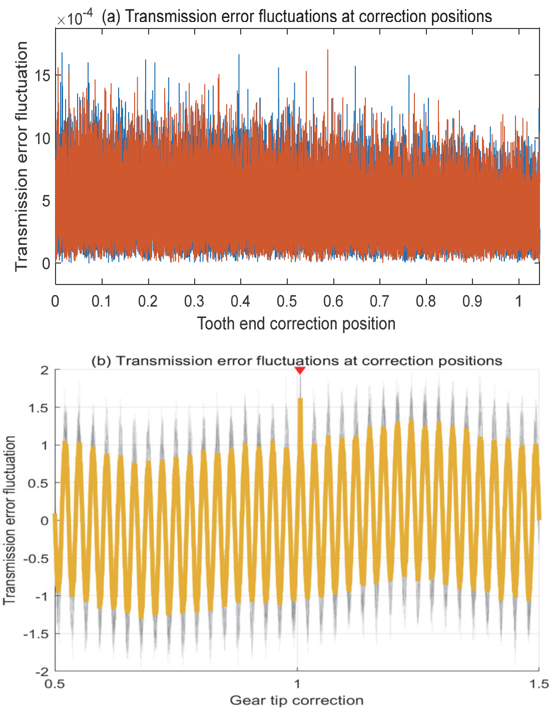

Figure 3 Transmission error fluctuation value corresponding to different modification parameters

Table 3 Value range of design variables

Gear wheel	Tip trimming amount	Top trim starting Angle	Amount of helix correction	Drum volume
Driving gear	21 - 28	35 - 39	18 - 27	6 - 17
Driven gear	26 - 31	22 - 25	8 - 15	8 - 14

Table 4 Optimal modification optimization scheme

Gear wheel	Tip trimming amount	Top trim starting Angle	Amount of helix correction	Drum volume
Driving gear	21.63	36.98	22.87	9.67
Driven gear	29.56	22.35	12.89	9.35

3.3 Gear Modification Calculation Based on Genetic Algorithm

1) Genetic coding to solve problems. Use binary code. If the modified parameter is 16 bits, the search range is 65535. Visible accuracy is sufficient.

2) Initialize the group. Since the modification parameter can be roughly determined by the empirical formula, the value interval of the modification parameter is taken as the boundary condition, and n is selected as the population size to randomly generate n binary encoded chromosomes with h_4 digits conforming to the boundary condition as the initial population, where $n = 30$ is taken.

3) Evaluate the group. Firstly, the modification quantities S_p, S_g, and the modification angles a_p, a_g are decoded according to the encoding mode. Because the gear has no vibration when the static transmission error is constant, it is reasonable to take the reciprocal of the static transmission error fluctuation of the gear as the adaptation value to evaluate the population. Define the fitness function as follows:

$$f = \frac{1}{\max(r) - \min(r)} \tag{7}$$

The maximum and minimum values of the transmission error r are calculated by substituting the decoding results into the finite element model.

4) Apply the selection operator. The probability of an individual $P(S)$ being selected is:

$$P(S_j) = f(S_j) \Big/ \sum_{i=1,\,\ldots,\,n} S_i, \quad j = 1, \ldots, n \tag{8}$$

5) Apply the crossover operator. Produce two new offsprings, but do not exchange before the first crossing point.

6) Then apply the mutation operator. If an individual has been selected, each of the selected individuals is mutated according to the mutation probability pm and inserted into the next generation.

7) When calculating to the K generation, if the population converges, it stops. If the termination condition is not met, proceed to Step 3).

4 RESEARCH ON GEAR MODIFICATION OPTIMIZATION BASED ON GENETIC ALGORITHM

4.1 Multi-objective Genetic Optimization Algorithm

(1) Problem coding: In fact, using different coding methods and different chromosome lengths will eventually affect the accuracy of the final solution. Both population and individual representations use real values, which have the advantage that there is no need to encode and decode chromosome strings, and the accuracy of the solution is higher than that of the binary method.

(2) Initial individual selection (generation of ancestors): Through the random number generation function, the advantage is that the initial individual has a general, can achieve global search. This chapter uses a multi-objective genetic optimization function that automatically generates an initial individual (ancestor).

(3) Determination of initial population (population) size: If the initial number of individuals is too small, the result of genetic algorithm will be worse, or even there is no solution to the problem. If too few individuals, the sampling points will be too few, and the diversity of individuals will be worse. If the number of individuals is too large, it will increase the amount of unnecessary computation. Studies have shown that the number of individuals between 40 and 220 will get a satisfactory result.

(4) Define fitness function: The fitness function is taken as the difference between the maximum and minimum values of the dynamic transfer error. Since the multi-objective genetic optimization function is to find the maximum value of the function, a negative sign needs to be added in front of the function. The fitness function is defined as follows:

$$f = -(\max(P(S_j)) - \min(P(S_j))) \tag{9}$$

(5) Determination of crossover probability Pc: The whole process of genetic algorithm is controlled by the probability Pc; if the Pc selection is too small, the calculation time will be too long, and the search process will stop. If the Pc selection is too large, those individuals with high fitness will cross operations with a greater probability, which will cause some chromosomes with high fitness to be damaged, affecting the effectiveness of the algorithm. Therefore, Pc = 0.5 - 0.9 is generally taken.

(6) Determination of variation probability Pm: Variation will affect the diversity of the population, and the appearance of variation operators actually further expands the search scope and improves the ability to search for the optimal solution; in fact, it also ensures that the genetic algorithm can search the whole feasible region. If the mutation probability Pm selection is too large, the search of genetic algorithm will become purposeless, so Pm = 0.001 - 0.01 is generally taken.

(7) Determination of crossover points and variation points: The system generates points of intersection and variation in a random manner.

(8) Determination of termination basis of genetic algorithm: The search ends when a better chromosome is found. The algorithm flow chart is shown in Fig. 4.

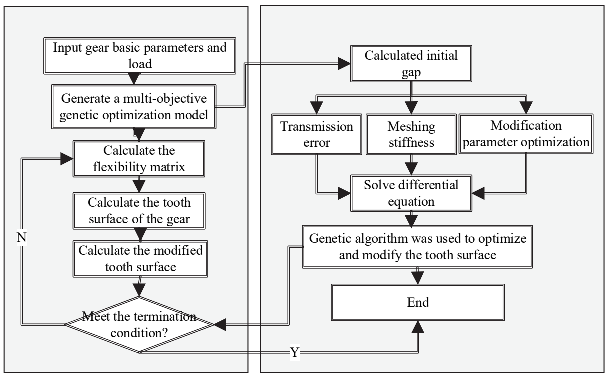

Figure 4 Flow chart of multi-objective genetic optimization algorithm for gear modification

Taking the tooth pair i as a reference, under the action of external force F, the coxal P and G of the gear are unchanged, and the geometric relationship between the meshing tooth pairs is as follows:

$$\chi_i + E_{pi} + E_{gi} = \chi_i + E_{pj} + E_{gj} + E^s_{pij} - E^s_{gij} \tag{10}$$

Transform into:

$$\chi_i - \chi_j = E_{pj} + E_{gj} - E_{pi} - E_{gi} + E^s{}_{pij} - E^s_{gij} \tag{11}$$

Relative to the theoretical tooth profile, if the material is removed from the tooth, then the denture profile error E is positive, otherwise, E is negative. According to the definition of the error function, it has the following properties:¨

$$\tilde{E}_{ij} = -\tilde{E}_{ji},\ \tilde{E}_{ij} = \tilde{E}_{kj} - \tilde{E}_{ki} \tag{12}$$

where i, j, and k are the numbers of different pairs of teeth. The expression of the comprehensive meshing stiffness K of the gear teeth is:

$$K = \frac{\sum_{i=1}^{n} K_i}{1 + \sum_{i=1}^{n} K_i \tilde{E}_{ki}} \tag{13}$$

4.2 Gear Modification Optimization Based on Genetic Algorithm

Using the multi-objective genetic optimization function, the evolutionary algebra was set to 150 generations. For the gear shown in Tab. 1, the tooth tip modification was adopted. According to the calculation model of the dynamic meshing parameters of the modified gear, Matlab was applied to program it, and the genetic algorithm was used to search in the feasible domain to obtain the gear modification parameters that minimized the difference between the maximum and minimum values of the dynamic transfer error, as shown in Tab. 5.

Table 5 Results of modification and optimization

Modified length / mm	Maximum amount of overhaul / um	Dynamic transmission error optimal value
3.323	6.54	–0.2543

The intermediate results of genetic algorithm search are shown in Tab. 6. It can be seen from the table that more accurate results can be obtained from the 14-th generation, so very accurate results can be obtained through the search of the 99-th generation.

Table 6 Intermediate parameters of the search process

Generation No.	Modified length / mm	Maximum amount of overhaul / um	Objective function
1	3.493	6.345	–0.2655
2	3.542	6.263	–0.2655
3	3.524	6.1787	–0.2564
4	3.545	6.4356	–0.2563
6	3.561	6.4534	–0.2653
9	3.369	6.3879	–0.2469
11	3.409	6.42	–0.2435
12	3.546	6.45	–0.2434
14	3.345	6.3898	–0.2433
15	3.345	6.3999	–0.2423
16	3.345	6.3999	–0.2423
24	3.345	6.3998	–0.2423
95	3.345	6.3998	–0.2423
99	3.321	6.3998	–0.2423

When the gear teeth are not modified, the value of the objective function (the difference between the maximum and minimum values of the dynamic transfer error) is 0.3872, and after the modification, the value of the objective function is 0.2423. As can be seen from Fig. 5, Fig. 5a represents the time history of the gear displacement without modification. Fig. 5b shows the displacement time history diagram of gear modification using the modification parameter with the minimum variation range of gear dynamic transmission error as the objective function.

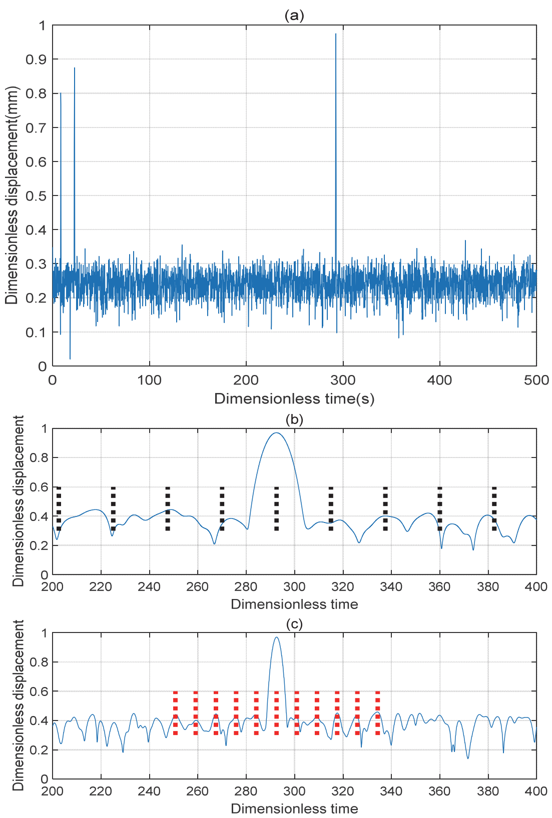

Figure 5 Displacement before and after gear modification - time history diagram

After modification, the variation range of gear tooth dynamic transmission error decreases. As can be seen from Fig. 5 and Fig. 6, the variation range of speed and acceleration of the modified gear also decreases compared with that of the unmodified gear. Therefore, the modification greatly improves the dynamic characteristics of the gear.

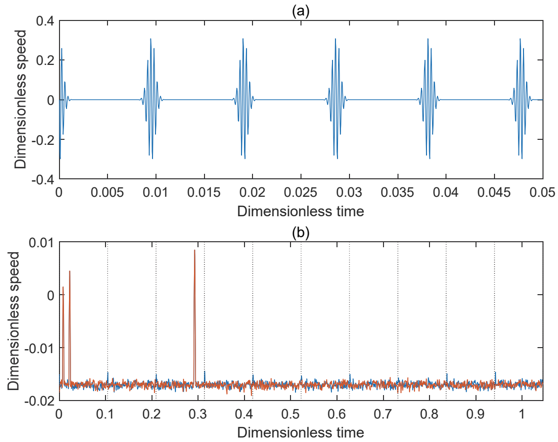

Figure 6 Speed-time history of gear before and after modification

It can be seen from the above figure that before and after the gear modification, whether it is the change of displacement, that is, the fluctuation range of dynamic transmission error, or the fluctuation curve of velocity acceleration, after the modification is obviously better than that before the modification. The modification not only eliminates the impact phenomenon in the meshing process, but also improves the dynamic performance of the gear to a great extent.

5 SIMULATION

Taking the standard mounting gear pair as an example, the accuracy grade is 5; Tab. 6 and Tab. 7 are related parameters, and the parameters of the optimization and modification curve are shown in Tab. 8. Fig. 8 shows the optimization performance before and after modification: without modification, the inlet and outlet end bears a large load; after modification, the meshing zone of the single tooth increases, and the load of the inlet and outlet end significantly decreases, as shown in Fig. 7a. Transmission error fluctuation drops to the bottom after modification, as shown in Fig. 7b; due to the reduction of the load on the entering end and the reduction of the contact degree after modification, the meshing stiffness decreases and the amplitude of the stiffness decreases, as shown in Fig. 7c. The reduction of the load on the rodent end and the amplitude of the bearing deformation are reduced, so the meshing impact is reduced (see Fig. 7d. As the meshing impact and the meshing stiffness fluctuation decrease, the torsional acceleration along the meshing line decreases after the modification, as shown in Fig. 7e. Similarly, the tangential translational vibration acceleration of the pinion after the modification decreases significantly, as shown in Fig. 7g. Without considering the meshing impact excitation, as the meshing stiffness fluctuation decreases, but the average meshing stiffness of the gear teeth decreases, the root-mean-square of the meshing linear acceleration after modification decreases less, as shown in Fig. 7f. Similarly, the tangential translational vibration acceleration of the pinion after modification decreases less, as shown in Fig. 7h. When stiffness excitation is only considered, the torsional vibration before and after modification is greater than the tangential vibration, as shown in Fig. 7f and Fig. 7h. After modification, the vibration decreases significantly at 0.5 and 1 frequency doubling, as shown in Fig. 7j. When meshing impact and stiffness excitation are considered, the tangential time-forward vibration is close to the torsional vibration, as shown in Fig. 7e and Fig. 7g, and the overall vibration decreases significantly after modification, as shown in Fig. 7i. The modification basically does not change the frequency composition, but can reduce the resonance frequency amplitude.

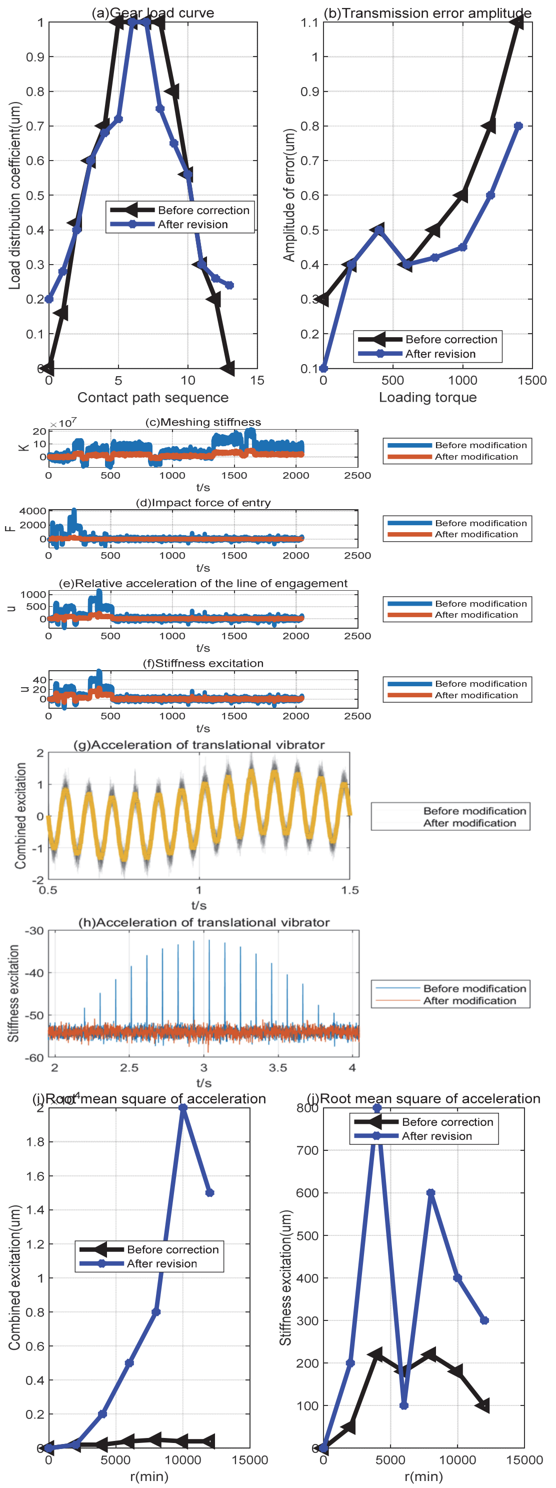

Figure 7 Spur gear modification optimization performance

Table 5 Basic parameters of spur gear

Number of teeth	Module / mm	Pressure Angle	Tooth width
18/46	9	22	76

Table 6 Basic parameters of dynamics

Bracing damping	Support stiffness	Big wheel load	Pinion speed
3.6 × 1000	6 × 109	860	2200

Table 7 Parameter results of optimization and modification curves

y_1 / um	y_2 / um	y_3 / um	y_4 / um
12	1.2	13	2.6

Fig. 8 shows the transmission error curve of gear pair after optimization, with the maximum value of 49.18 um and the minimum value of 48.25 um, and the transmission error increases as a whole compared with that before optimization, which is caused by the removal of gear materials in the shape modification optimization. However, the main index affecting the vibration and stability of gear system is transmission error fluctuation value, which is 0.75 um after optimization. Compared with before optimization, it is greatly reduced, and the smoothness of gear transmission is enhanced, and the optimization effect is good.

After optimization, the load distribution of the driving gear tooth surface is shown in Fig. 9. After optimization, the maximum normal load per unit length of the driving gear tooth surface of the output stage is 520.239 N/mm, which is significantly more reduced than the 663.421 N/mm before optimization. At the same time, the load distribution of the tooth surface is relatively uniform, and the larger tooth surface load is mainly distributed in the middle of the tooth surface with strong bearing capacity. The problem of partial load before optimization is solved effectively, and the bearing capacity of gear transmission is improved.

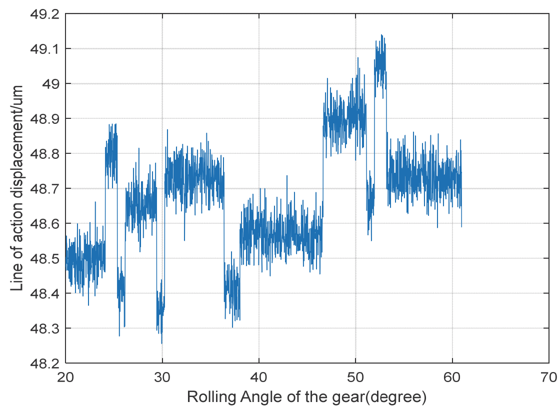

Figure 8 Transmission error after optimization

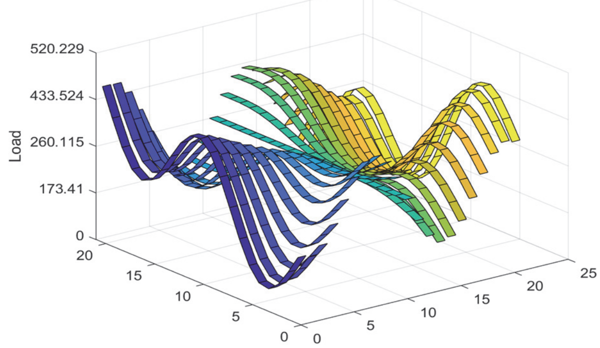

Figure 9 Normal load distribution of the tooth surface after optimization

The proposed genetic algorithm is used to optimize the tooth tip of the gear tooth. Using the calculation model of meshing stiffness of modified gear as mentioned above, Matlab software was applied to compile the program, and the maximum iteration number of genetic variation was set to 100, population number to 60, mutation rate and crossover rate to 0.85, the threshold of termination algorithm was 10^{-8}, and the search range of the maximum modification amount was (0 - 8.5 um). The search range of the modified length is (0 - 4.8 mm), and the optimization search process is shown in Fig. 10.

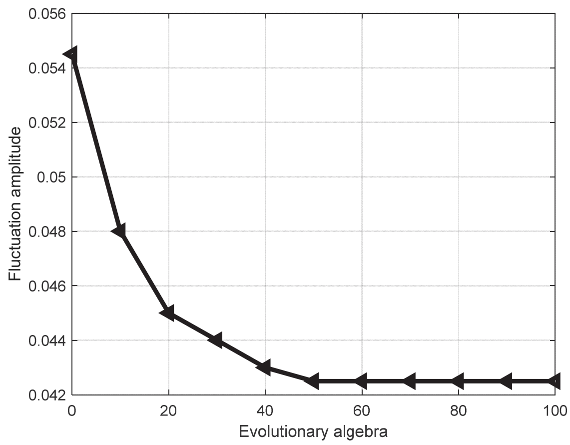

Figure 10 Genetic algorithm optimization search curve

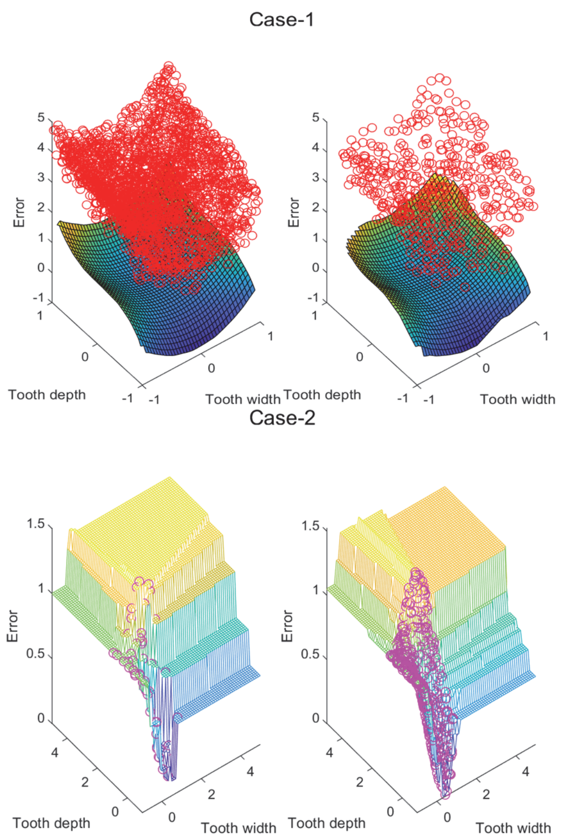

Figure 11 Difference surface between gear and face gear

Fig. 11 shows the above four groups: the difference surface of the tooth surface of an example gear. The modification amount of gear tooth surface is related to the preset long axis of the contact ellipse and the contact path. The smaller the length of the contact axis of the contact ellipse, the smaller the contact area of the gear teeth during meshing; the more tooth surface materials to be cut, the larger the modification amount. The direction of the contact path will affect the distribution on the gear tooth surface. The tooth surface modification amount of face gear is related to the preset geometric transmission error. The larger the geometric transmission error is, the more tooth surface materials need to be cut, and the larger the tooth surface modification amount of face gear. The modified tooth surface is composed of parabolic modified curve, so the difference surface of the gear is parabolic like. The geometric transmission error of Case-1 group is the second order, so the difference surface of the face gear is like parabola, and the difference surface of Case-2 group is like the fourth order curve, which is consistent with the type of geometric transmission error.

If the finite element method and genetic algorithm are directly used to optimize the shape, the total number of times to call the comprehensive stiffness of the gear with different shape parameters is 8000 times (a single calculation time is about 300 s); then it will require at least 26.81 d, while the algorithm in this paper only needs 2.24 h (a single mesh stiffness calculated by the model only needs about 1.006 s). The computational efficiency of the proposed algorithm is proved to be superior.

6 CONCLUSION

The modified optimization algorithm proposed in this paper adopts the multi-objective genetic optimization multi-response prediction model to solve the problem of implicit function and multi-response in the meshing stiffness calculation of gear modified optimization. By comparison with the finite element calculation of meshing stiffness, it is found that the maximum parameter error of the time-varying meshing stiffness function obtained by the multi-objective genetic optimization multi-response prediction model is 0.3872 (the difference between the maximum and minimum values of the dynamic transfer error), and the modified value of the objective function is 0.2423, which indicates a high calculation accuracy. The accuracy of multi-objective genetic optimization prediction model is verified. Compared with the unmodified gear response, the load at the inlet and outlet end of the modified gear is significantly reduced, so the meshing impact is significantly reduced. When only stiffness excitation is considered, the vibration decreases obviously at 0.5, 1 times the frequency after modification. When the meshing impact and stiffness excitation are considered, the tangential vibration is close to the torsional vibration, and the overall vibration decreases obviously after the modification. The algorithm in this paper has the best vibration reduction effect, which verifies the correctness and high efficiency of gear modification optimization based on genetic algorithm. Compared with the direct use of finite element method for gear modification optimization, the calculation time of the proposed algorithm is reduced from 26.81 d to 2.24 h, which proves the superiority of the calculation efficiency of the proposed algorithm. The analysis accuracy is affected by the optimal combination of modification parameters under the weighted comprehensive constant speed and acceleration conditions through the conversion cycle of five typical working conditions: start, acceleration, constant speed, deceleration and stop. At present, the multi-working condition comprehensive modification design requires a comprehensive weighted comprehensive combination of modification parameters under the five working conditions, which needs to be further optimized; this is also our next work plan.

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