IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 12, 2020, accepted October 28, 2020, date of publication November 3, 2020, date of current version November 12, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3035570

Design of Multi-Stage Gear Modification for New Energy Vehicle Based on Optimized BP Neural Network

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This work was supported by the National Natural Science Foundation of China under Grant 51765015.

ABSTRACT The NVH (Noise, Vibration, and Harshness) characteristics of new energy vehicles are the key indexes to measure interior comfort. The multi-stage gear reducer in the transmission system is the primary source of vibration and noise. The parameterized 3D model of the multi-stage gear transmission system of the new energy vehicle was established through Romax software, and the comprehensive gear modification method of the tooth direction combined with the tooth profile was built. Then a complete simulation analysis process is established to solve the maximum vibration acceleration of the multi-stage gear transmission system under constant speed condition, to obtain the simulation data of two-stage gear set under different modification parameters. The traditional BP (Back Propagation) neural network is optimized and improved through the optimal selection of network parameters combined with Bayesian regularization. Based on the optimized BP neural network, a modified parameter-vibration noise prediction model is constructed. Finally, the GA (Genetic Algorithm) optimization algorithm is used to solve the prediction model to obtain the optimal combination of modification parameters aiming at the minimum vibration acceleration, the effectiveness and reliability of the modified design are verified through actual simulation. It provides ideas and a basis for the research on vibration and noise reduction of multi-stage gears.

INDEX TERMS New energy vehicle multi-stage gear, optimize BP neural network, GA algorithm, modification design.

I. INTRODUCTION

In the running process of new energy vehicles, the vibration of the gear transmission system caused by alternate meshing will reduce the service life of gears, and the vibration noise will also have a great impact on the vehicle experience. Therefore, it is of great significance to study the noise reduction of the gear transmission system of new energy vehicles.

Due to the design error, machining error, and assembly error, the meshing impact and unbalanced load on the gear surface of the reducer of new energy vehicles will affect the NVH performance of the reducer, becoming the main source of vibration and noise. On the premise of ensuring the same function, the meshing gear was reasonably modified through the analysis of the structure of the reducer transmission system. It can reduce the transmission error, homogenize the load distribution on the tooth surface, and reduce the vibration and noise. Zhou *et al.* [1] analyzed the transmission gear with Romax software and optimized the gear modification parameters according to the gear modification theory and practical experience. The results show that the transmission error of the gear is reduced and the load distribution on the tooth surface is uniform. Wang and Huang [2] for cycloid gear, the profile modification design was carried out by using the dual-factor and multi-level equidistance modification method. The results show that the optimized parameter values make the tooth surface contact stress uniformly distributed. Wang *et al.* [3] took the automatic transmission of the pure electric vehicle as to the research object, analyzed and calculated the transmission system by establishing the transmission motor dynamic model, and modified the gear

The associate editor coordinating the review of this manuscript and approving it for publication was Agustin Leobardo Herrera-May.

under multiple working conditions to realize the gear noise reduction. A. Pavan *et al.* [4] modified the tooth profile of spur gears by micro-geometry to improve the life of electric and hybrid vehicles. Through contact analysis, a tooth profile improved spur gear with better running characteristics that were designed and optimized through experimental design. Ni *et al.* [5] proposed a new parabolic correction design method based on the concept of bevel gear generation. The results show that the parabolic correction can reduce the maximum contact force and root stress of the pinion under the same load. Combining TCA technology, LTCA technology, and gear dynamic performance, Wang [6] proposed a three-dimensional correction method to reduce helical gear vibration and achieved a good vibration reduction effect. (The LTCA and TCA methods are still limited to the field of kinetics. For mechanical characteristics such as gear transmission errors, it does not involve vibration and noise, and cannot directly reflect the influence of optimized noise. In this article, combined with neural network related theories, a scientific and reliable modified parameter-vibration acceleration prediction model is constructed, and intelligent algorithms are used to solve the prediction model to obtain the best combination of modified parameters.) Tang *et al.* [7] took the traction helical gear of CRH380A as an example to analyze its meshing characteristics. A modification plan is proposed, and the comparison of gear contact stress distribution before and after modification shows that the modification plan can effectively reduce gear meshing impact and transmission noise. Niu *et al.* [8] carried out shape modification and design analysis of gear based on KISSsoft software. The changes of contact stress, gear transmission error, and bending stress of tooth root before and after gear modification are obtained, which provides a theoretical basis for optimizing gear modification. Xu *et al.* [9] established the tooth profile modification model of the planetary gear system and analyzed the influence of modification parameters on the time-varying meshing stiffness and transmission error of the planetary gear system. The results show that gear repairing can effectively restrain the sudden change of meshing stiffness and significantly reduce the transmission error fluctuation. Zeng *et al.* [10] used a combination of positive isometric correction method and negative movement distance correction method to modify the tooth profile of the cycloid gear based on the transmission system of the motorhome reducer. The results show that the new method can better the modification of the requirements, to achieve an effective tooth profile engaging in the engagement area. Liu *et al.* [11] took the second gear helical gear pair of an electric vehicle gearbox as the research object and used KISSsoft software to optimize the modification of helical gear. The results show that the appropriate modification scheme can reduce the transmission error of gear and reduce vibration and noise.

In the actual gear modification design process, the traditional empirical formula or the engineer's experience is still used to calculate the gear modification amount. The former is tedious in a calculation, while the latter will inevitably result in deviation due to different gear application scenarios. With the popularization and popularization of computer-related technology, scholars at home and abroad have begun to combine optimization algorithms with the gear system model to study gear modification and noise reduction. Ma and Liu [12] established the simulation model of reducer gear pair in Romax, analyzed the influence of meshing error on meshing quality. The genetic algorithm is used to optimize the micro geometry modification of gear, and the effect of gear modification is verified. Jia *et al.* [13] proposed a new calculation method for calculating the modification of tooth width direction and tooth profile direction. By establishing the dynamic model of box transmission coupling, the actual meshing state of each gear pair is obtained by dynamic simulation, and then the actual meshing state is used as input to obtain the optimal modification parameters. Zhou *et al.* [14] studied the influence of tooth profile modification on the dynamic response of the planetary gear system and calculated the time-varying mesh stiffness (TVMs) and transmission error (TES) by a numerical model. Then the dynamic deviation factor is introduced to describe the dynamic response of PGT. The genetic algorithm is used to obtain the optimal TPM and minimize the dynamic load of the external and internal meshing. Zhang *et al.* [15] to reduce the vibration and noise of gear system, taking the fluctuation of dynamic transmission error as the index, the functional relationship between the modification amount and the transmission error fluctuation amount was constructed, and the optimal modification amount was obtained by solving the minimum value. Peng *et al.* [16] determined the optimal modification curve of gear pair according to the fluctuation minimization of static transmission error, and calculated the deflection of a single tooth by Hertz contact pressure analytic integration method based on the conformal mapping method, to realize noise reduction of gear pair. Han and Tian [17] proposed a gear modification optimization method based on genetic algorithm and energy method, which takes the gear transmission error as the direct optimization objective. A genetic algorithm is used to optimize the optimal modification parameters. The results show that the gear transmission error and gear meshing stress obtained by this method are minimum. Tang *et al.* [18] used finite element simulation data and RBF neural network to predict the corresponding relationship between gear modification parameters and gear transmission radiated noise. The multi Island genetic algorithm is used to optimize the gear modification parameters to minimize the gear transmission noise. Zhou *et al.* [19] established a simulation model for a double-clutch transmission gear system through Romax software, obtained the gear comprehensive modification parameter combination by sampling, and obtained the optimal modification parameters by combining neural network and genetic algorithm optimization. Xu *et al.* [20] proposed a method that combines tooth shape, tooth orientation modification, and the dual objective function to establish an optimization model to reduce the noise of gear reducer of electric vehicles. By optimizing the modification parameters, the transmission error is reduced and the contact stress is improved. Finally, the noise is effectively controlled. Fu *et al.* [21] combined LTCA technology with a genetic algorithm, and established an optimization model of face gear transmission vibration reduction correction. After optimizing the pinion and modifying the parameters, the fluctuation of the comprehensive meshing stiffness amplitude is significantly reduced, which effectively reduces the vibration and noise of the end gear transmission. Ji *et al.* [22] analyzed the static strength, load distribution, and transmission error of the two-stage reducer to improve the transmission performance of the gear. Using the combination of genetic algorithm V2 and Romax, several optimization methods of involute modification and lead modification are compared and analyzed. The results show that the use of lead crown modification and lead slope modification reduces the transmission error of the low-speed gear pair, improves the gear load distribution, and reduces vibration and noise.

Combining the optimization algorithm with the gear system model for gear modification and noise reduction is an effective way to optimize the design of gear modification parameters. Most of the existing research takes gear meshing stress or transmission error as the optimization goal, and few optimization methods take the reduction of gear vibration acceleration as the direct goal. The reason is that vibration and noise are the optimization target, which will involve many fields such as multi-body dynamics, modal theory, and howling noise. It is an interdisciplinary crossover difficulty. Moreover, there are only a few kinds of literature on gear profile modification and noise reduction of new energy vehicles by using an optimization algorithm. The reason is that the new energy automobile gear adopts the multistage gear transmission system, the gear modification involves many parameters, and the parameters will interact with each other. It is difficult to determine the mapping relationship of the noise size, and it is also difficult to construct the relevant mathematical relationship model. Some scholars only use the static and dynamic analysis to modify the multi-stage gear reducer and do not carry out further research on modification optimization. Through the parametric 3D modeling of a multi-stage gear transmission system of new energy vehicles by Romax software, the comprehensive modification method of tooth alignment and tooth profile is determined. Then a complete simulation analysis process is established to solve the maximum vibration acceleration of the multi-stage gear transmission system under constant speed condition, to obtain the simulation data of two-stage gear set under different modification parameters. The traditional BP neural network is optimized and improved through the optimal selection of network parameters combined with Bayesian regularization. Based on the optimized BP neural network, a modified parameter-vibration noise prediction model is constructed. Finally, with vibration reduction and noise reduction as the direct optimization goal, the GA optimization algorithm is used to solve the prediction model to obtain the optimal combination of modification parameters, the effectiveness and reliability of the modification design are verified through actual simulation.

II. PARAMETRIC DESIGN OF MULTI-STAGE GEAR TRANSMISSION SYSTEM

Taking the multi-stage gear transmission system of new energy vehicles as the research object, the parametric modeling of the gear transmission system is carried out by using Romax software. Through the selection of modification schemes, the determination of modification parameters, and the sampling range, combined with Romax software, the rapid parametric redesign of modified gear is realized.

TABLE 1. The main geometric parameters of the reducer gear set.

Name	Pinion 1	Wheel 1	Pinion 2	Wheel 2
Modulus m_n(mm)	2	2	3	3
Tooth face width b	50	50	70	70
Teeth Z	24	85	21	92
Pressure angle α_n(°)	20	20	20	20
Helix angle β(°)	24	24	16	16
Rotation direction	Right	Left	Right	Left

A. 3D MODEL CONSTRUCTION OF GEAR PAIR PARAMETRIC MODEL OF MULTI-STAGE REDUCER GEAR BASED ON ROMAX

Use Romax software as a platform to establish a parametric model of the gear transmission system of a new energy vehicle reducer. The chief geometric parameters of the gear transmission system are shown in Table 1. The 3D model of the multi-stage gear transmission system of new energy vehicles after construction is shown in Fig. 1.

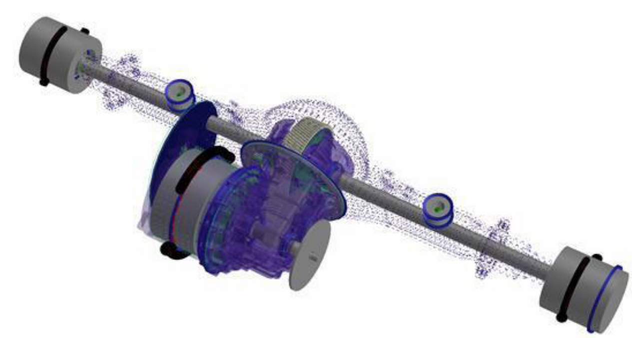


FIGURE 1. Three-dimensional model of multi-stage gear transmission system.

B. THE CHOICE OF MODIFICATION PLAN

Axial modification is to modify the tooth surface in the tooth direction. Its main purpose is to effectively improve the load distribution on the gear surface, increase the load-carrying capacity of the gear, and reduce the vibration and impact of the gear during transmission, thereby extending the gear life. The tooth end modification is suitable for situations where the amount of meshing misalignment has little effect on gear transmission. Tooth profile modification mainly includes tooth tip and tooth root modification. In the process of gear meshing transmission, the top of the tooth and the root of the tooth first come into contact, thereby generating a meshing impact. Tooth profile modification is to remove the interference part on the gear teeth, effectively reduce the impact vibration caused by the gear meshing in and out, and optimize the load distribution.

The comprehensive gear modification method of the tooth direction combined with the tooth profile is adopted based on the above analysis and related theory. Under the condition of ensuring the effectiveness of the modification, according to traditional experience and the actual workload, the gear modification is only for the driving gear of each gear pair, that is, the pinion.

C. DETERMINATION OF SHAPE MODIFICATION PARAMETERS AND SAMPLING RANGE

1) AXIAL MODIFICATION PARAMETERS

The determination of the drum shape is a key step in the axial modification, which can affect the quality of the later modification. The main method used is the combination of formulas (1) and (2) of the drum shape modification calculation formula and reference experience values:

$$C_a = 0.25b \times 10^{-3} + 0.5f_g \tag{1}$$

$$f_g = A\,(0.1b + 10) \tag{2}$$

Here: C_a is the amount of drum (μm); b is the tooth width (mm); f_g is determined by the accuracy of the tooth alignment error (μm); A is the coefficient determined by the accuracy class, the value under the accuracy level 6 is 2.0.

According to the calculation, it can be obtained that the tooth direction drum repair amount of the first-stage gear pair is 15μm, which is regarded as the maximum value, so tooth direction drum repair range is 0μm −15μm, and the tooth direction slope modification range is −15μm −15μm.

In the same way, it can be concluded that the amount of the second-stage gear pair is 17μm. Therefore, the modification range of the second-stage gear is 0μm −17μm, and the modification range of tooth inclination is −17μm −17μm.

2) TOOTH PROFILE MODIFICATION PARAMETERS

According to GB/Z6413.1-2003, the modification formula of gear tooth profile is obtained as follows:

$$C_\theta = \frac{K_A K_{\mathrm{mp}} F_t}{b \cos\alpha_t C_\gamma} \tag{3}$$

Here: K_A represents the service factor of gear working condition; K_{mp} is the branching coefficient; b is the tooth width (mm); α_t is the end pressure angle; F_t is the tangential force (N); C_γ is the meshing stiffness (N/(mm·μm)). Here we take K_A and K_{mp} as 1.

In general, the nominal tangential force of gear transmission is determined by the nominal power or torque transmitted by the gear. The nominal tangential force acting on the end face and cutting on the dividing circle can be calculated as follows:

$$F_t = \frac{2000T}{d} \tag{4}$$

Here: F_t is the tangential force (N); d represents the diameter of the gear index circle (mm); T represents the nominal torque (N·m).

Substituting the relevant parameters into the calculation, the tooth profile modification amount of the first-stage gear pair is 2.4μm, and the tooth profile modification amount of the second-stage gear pair is 12.4μm. Therefore, the tooth profile modification range of the first-stage gear pair is 0μm −2.4μm, and the tooth profile modification range of the second-stage gear pair is 0μm −12.4μm.

3) DETERMINATION OF SAMPLING RANGE

Based on the determination of the parameters under the multi-stage gear pair comprehensive modification mode, the first- stage gear tooth modification drum amount, the first-stage gear tooth inclination amount, the first-stage gear tooth profile modification amount, the second-stage gear tooth modification drum amount, the second-stage gear tooth inclination amount, and the second-stage gear tooth profile modification amount are selected as the sampling test data combination. The modification sampling range is shown in Table 2.

TABLE 2. Sampling range of modification parameters.

Modification parameter name	Value range(μm)
The first-stage drum gear tooth repair amount	0-15
The first-stage gear tooth inclination amount	-15-15
The first-stage gear tooth profile modification amount	0-2.4
The second-stage drum gear tooth repair amount	0-17
The second-stage gear tooth inclination amount	-17-17
The second-stage gear tooth profile modification amount	0-12.4

III. SIMULATION ANALYSIS OF MULTI-STAGE REDUCER GEAR TRANSMISSION SYSTEM

Under the constant speed condition, which accounts for the largest proportion in the operation of new energy vehicles, the dynamic analysis and calculation of the multi-stage gear transmission system model including gear pair, bearing, and box body before modification is carried out. It includes unit load analysis, transmission error analysis, modal analysis, bearing contact force analysis, box vibration acceleration

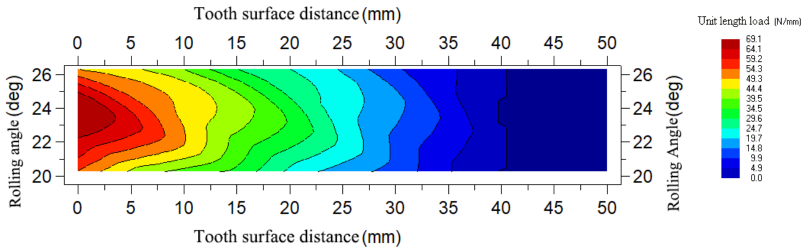


FIGURE 2. Nephogram of load analysis per unit length of wheel 1.

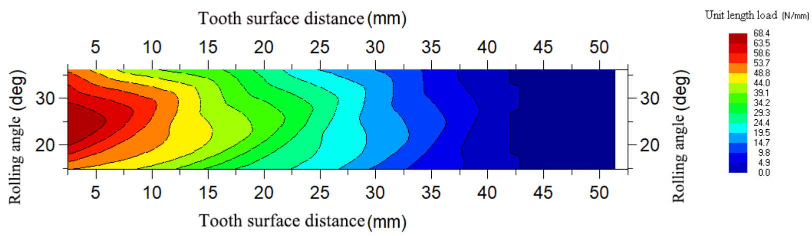


FIGURE 3. Nephogram of load analysis per unit length of pinion 1.

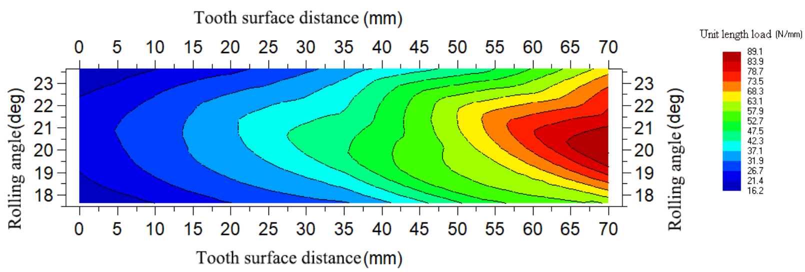


FIGURE 4. Nephogram of load analysis per unit length of wheel 2.

analysis, and gear whistling noise analysis. It is prepared for the subsequent modification and provides the basis for the effective comparison of the modification optimization. The following analysis takes the stable working condition as an example to analyze the gear transmission system of the multi-stage reducer. The main parameters of stable working conditions are motor output torque: 42.2N·m, motor output speed: 5719.2rpm, power: 25.3KW.

A. UNIT LOAD ANALYSIS

Unit load analysis is one of the significant indicators for measuring the effect of noise reduction models, which can directly reflect the effect of contact spots and provide a critical reference for our subsequent modification and optimization. Generally speaking, the unit load distribution of a gear transmission system should be as uniform as possible.

To facilitate the analysis and calculation, the unit load of the gear transmission system is usually calculated by the load per unit length along the contact line of the tooth surface. The average load P (N/mm) per unit length of the contact line along the tooth surface is as follows:

$$P = \frac{F_n}{L} \tag{5}$$

Here: F_n is the normal load acting on the contact line of tooth surface (N); L is the length of contact line along the tooth surface (mm).

Based on the above principles and formulas, with the help of Romax software, the unit load analysis of the transmission system of new energy vehicle multi-stage reducer is carried out, and the cloud chart of unit length load analysis of multi-stage gear is obtained. The unit length load distribution of the large gear and the small gear of the first-stage gear set are shown in Fig. 2 and Fig. 3, and the unit length load analysis of the large gear and small gear of the second-stage gear set is shown in Fig. 4 and Fig. 5.

According to the comprehensive analysis in Fig. 2 to Fig. 5, the contact spot formed by the first stage gear set under constant speed condition shows that the stress load on the left side of the gear is the largest. The maximum load per

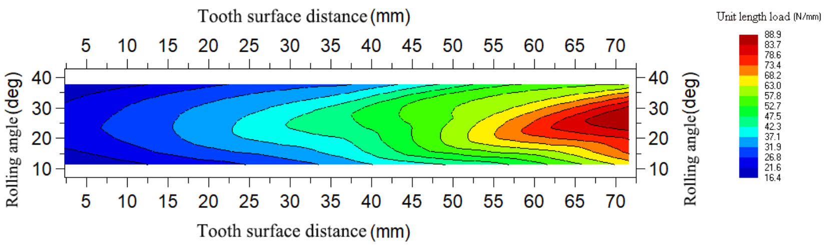


FIGURE 5. **Nephogram of load analysis per unit length of pinion2.**

unit length of pinion 1 is 68.4 N/mm, showing a deep red color. However, the load on the right side of the gear is the smallest with a load of 0 N/mm. From the contact spot results, the large and small gears of the first-stage gear pair have serious eccentric loads during the meshing process, which will make the gear system more likely to generate impact and vibration noise during the meshing process. Similarly, the contact spot formed by the second-stage gear pair shows that the left side of the gear receives the least stress load, and the minimum load per unit length of pinion 2 is 16.4 N/mm, which is dark blue. The maximum stress load on the right side of the gear is 88.9 N/mm.

B. TRANSMISSION ERROR ANALYSIS

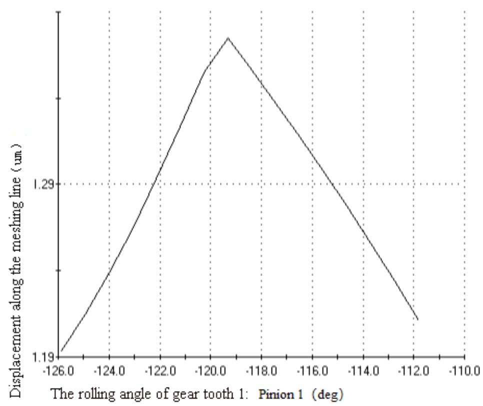
Transmission error is the main excitation source of gear whistling, which is composed of the static transmission error and dynamic transmission error. The static transmission error refers to the error caused by the actual production and processing of the gear, while the dynamic transmission error refers to the error caused by the deformation of the working face under the external load.

In Romax software, the static analysis of the gear transmission system is carried out, and then the transmission error analysis of the gearbox is carried out. The transmission linear error results of the first and second-stage gear sets of the gear transmission system are obtained. The 2D drawing report is shown in Fig. 6, and the transmission linear error data table is shown in Table 3.

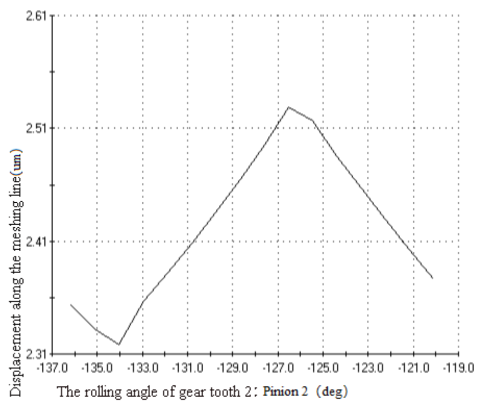
Analysis of the above transmission error shows that the transmission error image intercepted by the Romax software is only a representative segment of the gear meshing cycle. The linear transmission error is the maximum displacement along the meshing line minus the minimum. The transmission error of the first stage gear set is 0.181μm, and that of the second stage is 0.210μm. The following gear modification should reduce the transmission error, to reduce the vibration and noise.

C. GEARBOX MODAL ANALYSIS

The essence of the modal analysis of the multi-stage gear transmission system of a new energy vehicle is to analyze the natural frequency and mode shape of the multi-stage reducer transmission system itself. Therefore, the modal analysis is also the basis of other dynamic analysis. The natural frequency can be understood as the frequency of the gear pair meshing of the transmission system under the specified working conditions. The modal vibration mode



(a) Transmission linear error of first-stage gear set



(b) Transmission linear error of the second-stage gear set.

FIGURE 6. **Linear error diagram of gear set transmission.**

TABLE 3. **Gear set transmission linear error data.**

	First-stage gear set		Second-stage gear set	
	Rolling angle (deg): Pinion 1	Displacement along the meshing line (μm)	Rolling angle (deg): Pinion 2	Displacement along the meshing line (μm)
Maximum value	-111.81	1.37	-120.09	2.53
Minimum value	-125.87	1.19	-136.16	2.32
Range	14.06	0.181	16.07	0.210

can be understood as the vibration of gear pair meshing or the vibration of rotating shaft radiated to the whole system, to deform its shape, that is, the state of the transmission system in this specific mode.

According to the dynamic equation of the undamped free vibration system in modal theory, by Fourier transformation, it can be obtained as follows:

$$[K]\{\Phi i\} = \omega i^2[M]\{\Phi i\} \tag{6}$$

Here: M is systematic mass matrix, K is stiffness matrix, Φi is time-invariant eigenvector. The eigenvalue ωi is systemic natural frequency.

The fundamental purpose of the modal analysis of the new energy vehicle multi-stage reducer transmission system is to analyze and explore the vibration of the new energy vehicle multi-stage reducer gearbox under specific modal conditions. When the box is vibrated under the impact of dynamic load, generally speaking, the resonance generated by the first few modes is more dangerous and has a more serious impact on the dynamic performance of the box. Due to the complex coupling between frequencies in the high-order frequency range, it is distinctly difficult to accurately identify modal parameters. Besides, high-order modes have little effect on the dynamic performance of the cabinet. Therefore, this study conducted a modal analysis of the gearbox from the first ten modes. According to the above modal analysis theory and calculation formula, combined with the modal analysis module of Romax software, the first ten-order modal data of the gearbox are integrated into Table 4, and the first-order vibration mode of the gearbox is shown in Fig. 7.

TABLE 4. The first ten modal data of the gearbox.

Order	Frequency (Hz)	Order	Frequency (Hz)
1	3806.44751	6	5214.54785
2	3808.33643	7	5411.71338
3	3960.4043	8	5997.50244
4	4013.15771	9	6318.69922
5	4849.1084	10	6620.55176

Analyzing the modal data, we can see that under constant speed conditions, the gear meshing frequency is equal to the gear's rotational frequency (rpm or Hz) multiplied by its number of teeth, according to the calculation, the meshing vibration frequency of the first-stage gear pair is 2287.60 Hz, and the meshing vibration frequency of the second-stage gear pair is 565.25 Hz. Compared with the box modal frequency, it can be seen that the modal frequency of the gear pair avoids the resonance zone. Also, it is necessary to consider whether the multiplier of the meshing frequency avoids the resonance zone. By calculating the frequency multiples of the meshing vibration frequency of the first-stage gear and the second-stage gear, compared with the modal frequencies in the above table, the modal frequencies have avoided the resonance zone.

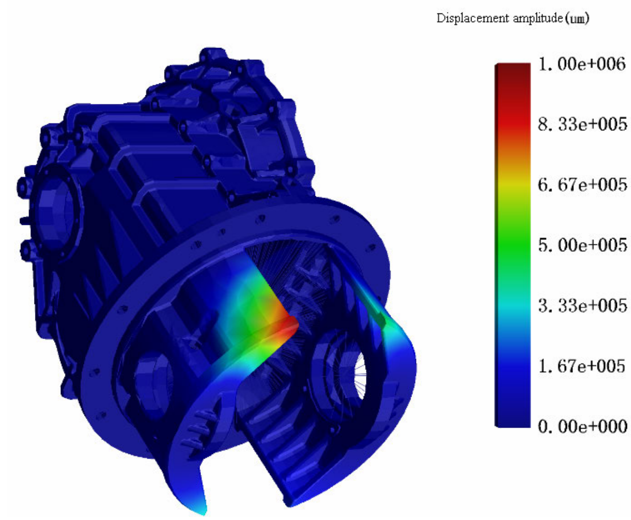


FIGURE 7. The first-order mode of vibration of gearbox.

D. BEARING CONTACT FORCE ANALYSIS

As the most significant supporting component in the gear transmission system, the bearing is used to connect the transmission shaft and the entire box. The vibration generated by the gear meshing or the rotation of the main shaft will be transmitted to the bearing and finally to the box. Therefore, the analysis of the bearing in the transmission system is also very important for the entire dynamic analysis.

Six bearings in the gearbox are selected as follows: rolling bearing 1 (radial ball 6310), rolling bearing 2 (cylindrical roller NU209), rolling bearing 3 (tapered roller bearing 33110), rolling bearing 4 (tapered roller bearing 33110), rolling bearing 5 (tapered roller bearing 32013X), rolling bearing 6 (tapered roller bearing 33110). Under the condition of constant speed, gear meshing is the main internal excitation. Analyze the bearing contact force of the 6 bearings in the new energy vehicle multi-stage gear transmission system at the 24-order frequency. The peak corresponding frequency of each rolling bearing is integrated into Table 5, and the contact force of rolling bearing 1 is shown in Fig. 8.

From the above analysis, we can see that the bearing forces of six bearings are very high near 2300 Hz and 4200 Hz, which can easily excite the vibration of the system. Bearing 1, 3, and 4 have peak values at about 4126 Hz, which is close to the fourth modal frequency of the box. Therefore, vibration noise is most easily generated at 4126 Hz. At 560 Hz, the bearing contact force is also relatively high, and the meshing frequency of the secondary gear is 565.25 Hz, which indicates that vibration noise is also easy to be generated at this location.

TABLE 5. Rolling bearing peak corresponding frequency table (double peak frequency value).

Rolling bearing serial number	Corresponding frequency value (Hz)	
1	2260	4220
2	2320	4580
3	2300	4180
4	2320	4100
5	2280	4600
6	2280	4900

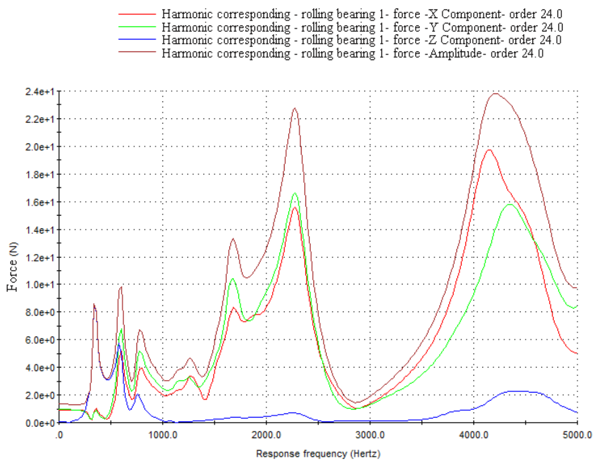


FIGURE 8. Rolling bearing 1 contact force diagram.

E. GEARBOX VIBRATION ACCELERATION ANALYSIS

The vibration acceleration analysis of the gear transmission system is the core of the whole dynamic analysis, and also the core of the noise problem of the whole new energy vehicle multi-stage reducer transmission system. To analyze the vibration acceleration of the whole gear transmission system, it is necessary to select nodes in the gearbox for data measurement.

To analyze the vibration of the whole gearbox, eight different types of gear nodes were selected. They are node 1 (rolling bearing 3), node 2 (rigid connection 14), node 3 (rolling bearing 2), node 4 (rolling bearing 1), node 5 (rolling bearing 6), node 6 (rolling bearing 5), node 7 (rolling bearing 4) and node 8 (rigid connection 10). The specific node location is shown in Fig. 9, and the selected 8 nodes are all over the whole box. The amplitude curve of vibration acceleration and frequency corresponding to the eight nodes on the box body under the excitation of two-stage gear meshing transmission error is shown in Fig. 10.

It can be seen from Fig. 10 that the peak vibration acceleration of the box at each node occurs at 3840 Hz, the vibration acceleration of node 1 and node 4 is the largest, while that of node 2 and node 8 is the minimum.

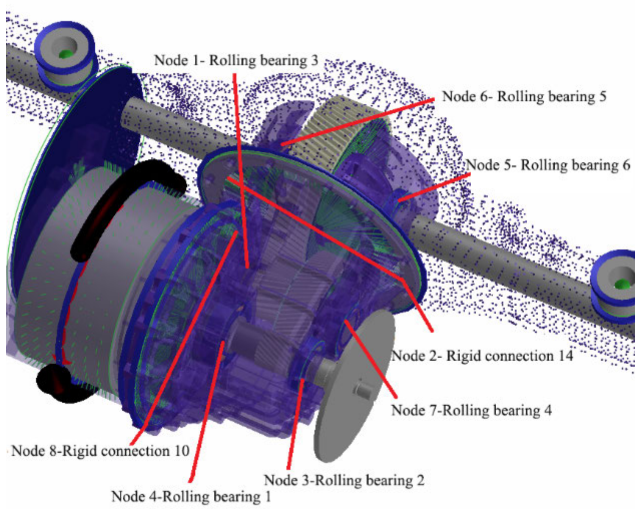


FIGURE 9. Location map of each node.

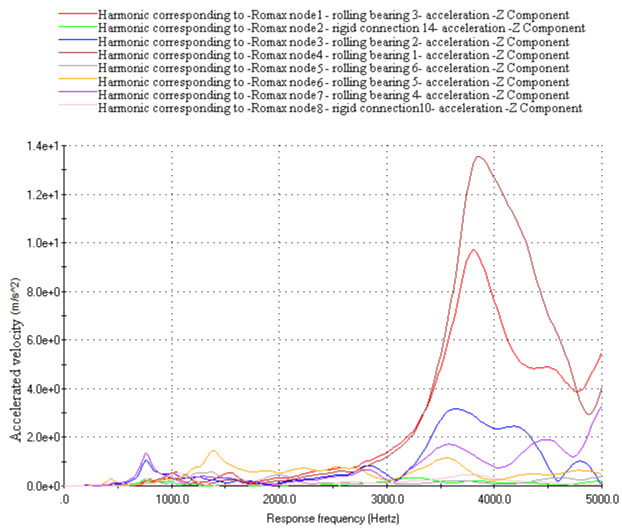
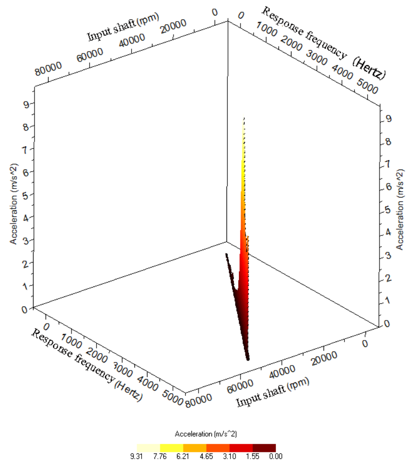


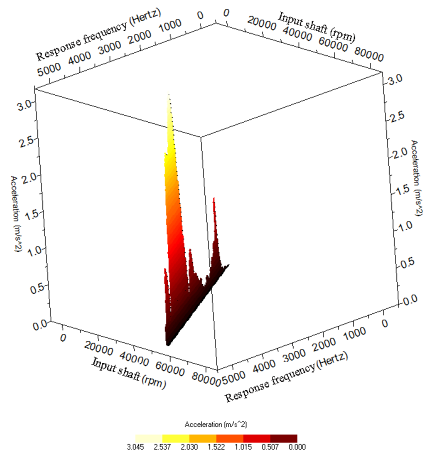
FIGURE 10. Vibration acceleration of each node box.

F. GEAR HOWLING NOISE ANALYSIS

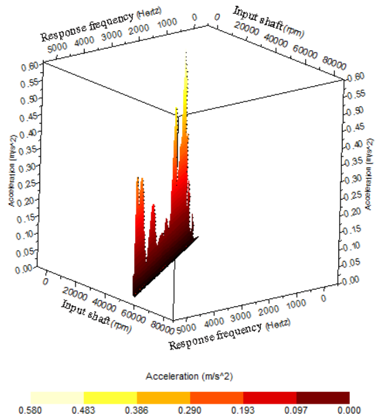
The traditional analysis method of the noise spectrum is not suitable for the analysis of noise howling in the transmission system of the multi-stage reducer of new energy vehicles. Because the rotation speed of the new energy vehicle motor is not always fixed at a certain value in the actual working environment, this means that the rotation speed of the input shaft to which the motor is connected is not fixed at a certain value. This article uses a more accurate method to measure the vibration state of the transmission system of the multi-stage reducer of a new energy vehicle-the order analysis method, that is, the method of controlling the constant increment. The steady-state signal in the time domain of the gear system is stripped from the unstable signal. Because the whistling noise of the gear is inseparable from the running speed of the gear pair, the characteristic frequency and rotation frequency of the signal will change



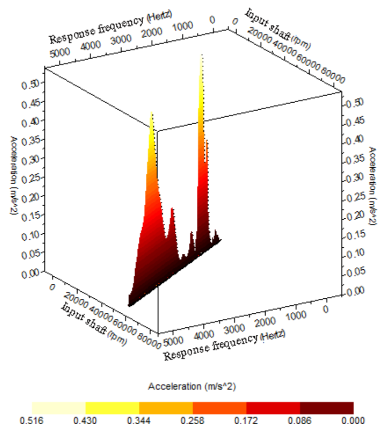
(a) Howling noise acceleration of node 1.



(b) Howling noise acceleration of node 3.



(c) Howling noise acceleration of node 5.



(d) Howling noise acceleration of node 8.

FIGURE 11. Howling noise acceleration of each node of the gearbox before modification.

with the continuous change of the speed. The ratio of the vibration characteristic frequency of the system to the rotational speed of the motor shaft will not change, and this constant ratio is the order. The relationship between speed and sampling signal frequency is as follows:

$$o = \frac{f \times 60}{n} \tag{7}$$

Here: o is the order; f expressed as the frequency value of the signal; n is expressed as speed (r/mm).

Combining the analysis results under the two-stage gear meshing excitation, select node 1 (rolling bearing 3), node 3 (rolling bearing 2), node 5 (rolling bearing 1), node 8 (rigid connection 10), and find their vibration acceleration waterfall diagram under the excitation of two-stage gear meshing transmission error, as shown in Fig. 11 (a-d):

It can be seen from Fig. 11(a-d) that under the excitation of two-stage gear meshing transmission error, the maximum vibration acceleration of node 1 is 9.31 m/s^2, and the maximum vibration acceleration of node 3 is 3.045 m/s^2. The maximum vibration acceleration of node 5 is 0.58 m/s^2, and the maximum vibration acceleration of node 8 is 0.516 m/s^2.

IV. PARAMETER SAMPLING AND VIBRATION NOISE RESULTS BASED ON OPTIMAL LATIN HYPERCUBE

With the help of the Isight platform to uniformly sample each modification amount within the sampling range, obtain different combinations of data between various modification parameters. The gear modification model is established in Romax software by combining various modification parameters, and the corresponding maximum vibration acceleration is obtained through the simulation process of dynamic analysis.

Perform a sampling combination of the modified data for each modification parameter within the sampling range obtained in Table 2 in Section II-C3. With the aid of the Optimal Latin Hypercube Sampling Module (OptLHD) in Isight software, the modified parameter combination data is sampled.

The basic working principle of Latin hypercube is that in n-dimensional space, each coordinate interval is evenly divided into m intervals to form a Latin hypercube design with n-dimensional space and m number of samples, denoted as m×n LHD, the samples drawn with LHD have the good space-filling ability and fitting nonlinear response-ability, but its disadvantages are uneven distribution of test points and non-repeatability of experiments. The basic principle of the optimal Latin hypercube method is similar to that of the Latin hypercube, but space is distributed with equal probability, thereby improving the unevenness of the Latin hypercube test points and improving the fitting accuracy of the experimental factors. Due to the small sampling range of modification parameters and the complexity of obtaining the maximum vibration acceleration data needed in the follow-up study, 200 groups of modified parameter combination data were sampled as the sample data. Using the DOE module of Isight software, set the number of samples to 200 groups, and set the sampling range of modification parameters, run the optimal Latin hypercube sampling method to complete the sampling, and get the combined data under the range of modification parameters.

The 200 sets of modification parameter combinations obtained by sampling are sequentially imported into Romax software to construct their new energy vehicle multi-stage gear system modification models. And according to the simulation analysis process of dynamic analysis, the maximum vibration acceleration of the selected 4 nodes is obtained. The data of the maximum vibration acceleration of the gear under each modification parameter combination is shown in Table 6. It can be seen from the analysis of the vibration acceleration of each node under different modification parameter combinations that the maximum vibration acceleration generated by node 1 is always at the maximum of the four nodes. Considering the accuracy of the subsequent research, the vibration acceleration of node 1 is taken as the vibration noise represents nodes.

V. MULTI-STAGE GEAR VIBRATION NOISE PREDICTION MODEL BASED ON OPTIMIZED BP NEURAL NETWORK

A. BASIC THEORY OF BP NEURAL NETWORK

BP neural network is a multi-layer neural network based on error back propagation for network training. It is also one of the most widely used network models in various fields. The BP neural network does not need to know the mathematical expression of the mapping relationship between the input and the output, builds a model by continuously learning the data to achieve the purpose of prediction.

In practical applications, the neural network method has more advantages than linear regression and curve-fitting in processing this kind of data. It can not only fit a smooth curve but also avoid the situation where the data has extreme points. The BP neural network has a structure of bias, no less than 1 S-type hidden layer, and a linear output layer, which can approximate any nonlinear mapping relationship. BP neural network also has some shortcomings, such as a local minimization problem, slow convergence speed, and different structure choices. However, considering the BP neural network comprehensively is the best choice for constructing a prediction model between the modification parameters and the noise and fitting the two data.

B. OPTIMIZED BP NEURAL NETWORK MODEL CONSTRUCTION

To explore the corresponding relationship between multi-stage gear modification parameters and vibration noise, 200 sets of gear modification parameter combinations sampled in Section IV are used as the input data of the prediction model. Taking the vibration acceleration of the representative nodes of vibration and noise as the output data of the prediction model, the vibration and noise prediction model of the multi-stage gear reducer of new energy vehicles is established. Using Bayesian regularization combined with the optimal selection of network parameters to optimize the BP neural network to obtain the required vibration and noise prediction model.

For 200 data sets, 80% of the data sets are randomly selected as the training set to train the BP neural network model, and the remaining 20% are used as the test set to verify the model.

In terms of the model, 6 shaping parameters are selected as the input of the neural network model, and one of the four nodes is selected as the output of the maximum vibration acceleration to construct the vibration and noise prediction model:

$$a = f\,(L_1, L_2, L_3, L_4, L_5, L_6) \tag{8}$$

Here: a is the noise vibration acceleration (m/s^2);L_1 is the amount of first-stage gear tooth direction repair drum (μm); L_2 is the first-stage gear tooth inclination amount (μm);L_3 is the first-stage gear tooth profile modification amount (μm);L_4 is the amount of second-stage gear tooth direction repair drum (μm);L_5 is the second-stage gear tooth inclination amount (μm);L_6 is the second-stage gear tooth profile modification amount (μm).

The method of optimally selecting network parameters takes the fitting accuracy of the BP neural network on the training set as the objective function and uses the optimally selected traversal method to continuously find the optimal number of hidden layers and the number of neurons. Through traversal for multiple pieces of training, the appropriate network parameters are finally obtained.

The basic idea of Bayesian regularization is [23]: in neural networks, the number of training samples is determined. When a certain number of samples are used for neural network training, the generalization ability of the neural network is closely related to the structure of the network. The purpose of establishing the neural network is to find an effective function that approximates the sample and to make the error function as small as possible. The error function generally adopts the mean square error function. Here, assuming that the error function is E_Q, then:

$$E_Q = \sum\nolimits_{i=1}^{y} (t_i - a_i)^2 \tag{9}$$

Here: Q is the number of samples; t_i is the expected output value; a_i is the actual output value.

Regularization is to add some "standards" to the training objective function so that it cannot exceed the "standards".

TABLE 6. The maximum vibration acceleration data of each node of the gear under each modification parameter combination (partial).

No	The first-stage drum gear tooth repair amount (μm)	The first-stage gear tooth inclination amount (μm)	The first-stage gear tooth profile modification amount (μm)	The second-stage drum gear tooth repair amount (μm)	The second-stage gear tooth inclination amount (μm)	The second-stage gear tooth profile modification amount (μm)	Node 1 (m/s^2)	Node 3 (m/s^2)	Node 5 (m/s^2)	Node8 (m/s^2)
1	7.839	0.23	1.435	14.352	-2.31	5.608	14.71	11.56	8.87	1.835
2	9.799	12.29	2.376	4.955	-11.7	5.047	7.34	3.751	3.081	0.737
3	7.688	10.48	0.265	8.286	-14.1	2.306	7.3	4.04	3.426	0.773
4	10.854	5.2	0.121	9.141	14.78	3.863	9.2	6.65	5.58	1.161
5	4.07	4.3	0.699	15.804	-14.95	4.673	15.36	11.93	9.24	1.92
6	10.327	7.31	1.869	14.437	-4.19	0.249	12.59	8.13	6.92	1.491
7	9.95	11.98	0.844	8.714	1.45	0.623	6.09	3.185	2.454	0.519
8	9.347	-1.58	1.218	4.528	-0.43	2.056	3.719	1.317	0.92	0.1763
9	2.714	-3.09	1.688	4.357	-16.66	6.73	9.4	5.4	3.642	0.938
10	0.151	-9.57	0.217	8.884	2.48	5.421	10.54	7.82	6.27	1.318
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
200	14.171	5.8	0.35	8.848	-4.87	10.655	15.58	12.38	9.4	1.93

The regularization method refers to the addition of a term to limit the complexity of the approximation function on the basis of the standard error function, that is, after regularization, the network performance function becomes:

$$F = \tau E_Q + \upsilon E_W \tag{10}$$

$$E_W = \frac{1}{N}\sum_{i=1}^{\eta} \chi_i^2 \tag{11}$$

Here: E_W is the sum of squares of network weights; χ_i is the neural network connection weight; N is the number of neural network connection weights; E_Q is the sum of the squares of the network output and the target value; τ and υ are the parameters of the objective function. In the Bayesian framework, the network connection weights are regarded as random variables, the parameters τ and υ when the objective function is the smallest can be obtained by maximizing the posterior probability. It can be obtained:

$$\tau = \frac{\psi}{2E_W}, \upsilon = \frac{Q-\psi}{2E_Q} \tag{12}$$

Here: ψ represents the number of effective weights of network parameters in the training sample. ψ can be optimized by Bayesian regularization.

The optimized BP neural network model is obtained through the optimal selection of network parameters and Bayesian regularization. The fitting accuracy graph and convergence effect graph of the model to the training set are shown in Fig. 12 (a) and Fig. 12 (b). And use the test set to evaluate the performance of the model to verify the predictive ability of the model. The fitting accuracy diagram is shown in Fig. 12 (c). The overall fitting effect of the model on the data is shown in Fig. 12 (d) and Fig. 12 (e).

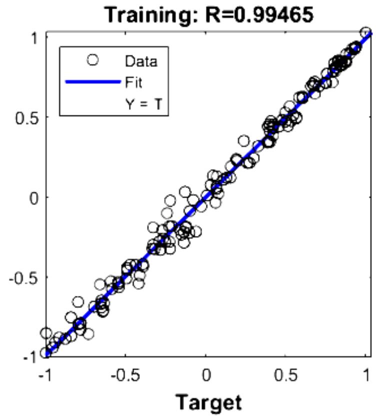
By analyzing the above visualization results in Fig. 12 (a-e), it can be seen that the BP neural network model optimized by Bayesian regularization combined with optimal selection of network parameters has very high fitting accuracy and very fast convergence speed. It can be seen from Fig. 12 (a) and Fig. 12 (b) that the model's fitting accuracy to the training data has reached 99.46%, and it has a very fast convergence speed. The test set also showed good generalization ability, with a prediction accuracy of 99.03%. It can be seen intuitively from the overall fitting effect (Fig. 12 (d) and Fig. 12 (e)) that the optimized model has a good fitting effect on the gear modification parameter-vibration and noise data set. It shows that the model has the good predictive ability, and this optimization model can be used as a follow-up study on the optimization of multi-stage gear modification parameters of new energy vehicles.

C. DATA FITTING COMPARISON WITH OTHER COMMON PREDICTION MODELS

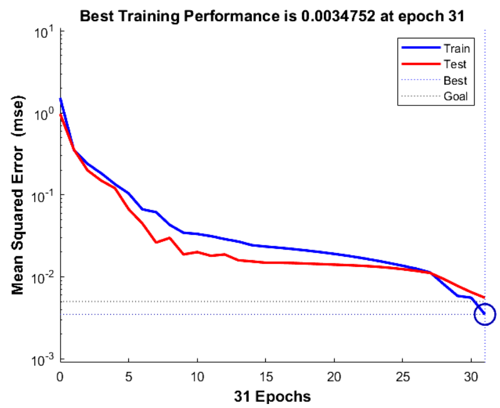
Based on the same data set, use the RBF neural network and XGBoost machine learning algorithm to establish the corresponding prediction model, and compare it with the optimized BP neural network model to prove the superiority of the optimized BP neural network model in data fitting ability.

1) RBF NEURAL NETWORK FITTING

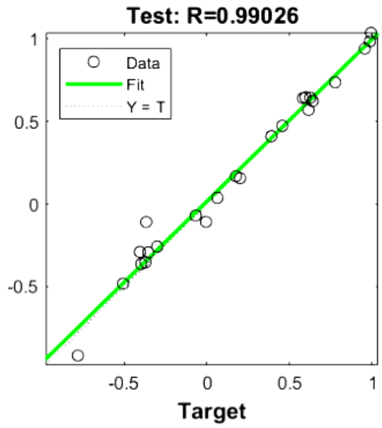
The RBF neural network is a feedforward neural network. Its basic principle is: RBF is used as the "base" of the hidden unit to form the hidden layer space, and the input vector is directly mapped to the hidden space instead of the



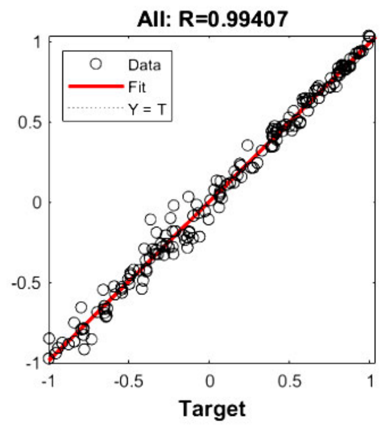
(a) Model training set fitting accuracy diagram.



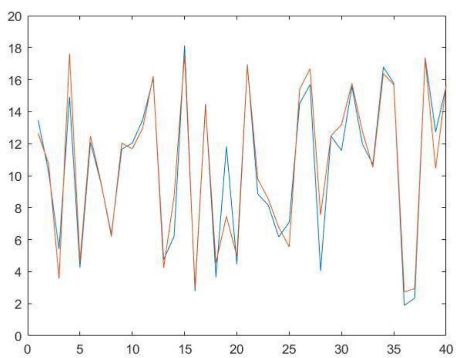
(b) Model convergence effect diagram.



(c) Model test set fitting accuracy diagram.



(d) Overall model fitting accuracy diagram.



(e) Model fitting effect diagram.

FIGURE 12. **Summary of model fitting diagrams.**

weight connection. The relationship is established with the determination of the RBF center.

Use the same data set to construct the corresponding RBF neural network model. The convergence effect of the model on the data set is shown in Fig. 13, and the fitting effect is shown in Fig. 14.

It can be seen from the figure that the RBF neural network converges slowly to the data set, and its generalization ability on the data is very poor, which cannot achieve the purpose of vibration and noise prediction in this study.

2) XGBOOST MACHINE LEARNING ALGORITHM FITTING

To verify the superiority of the optimized BP neural network constructed in this study, we used the widely used open-source machine-learning algorithm to construct a prediction model and compared the fitting accuracy. In the choice of the machine learning algorithm, XGBoost (full name eXtreme Gradient Boosting) was chosen to fit the data. The XGBoost machine learning algorithm is used to fit the obtained data. The accuracy of the model is shown in Fig. 15.

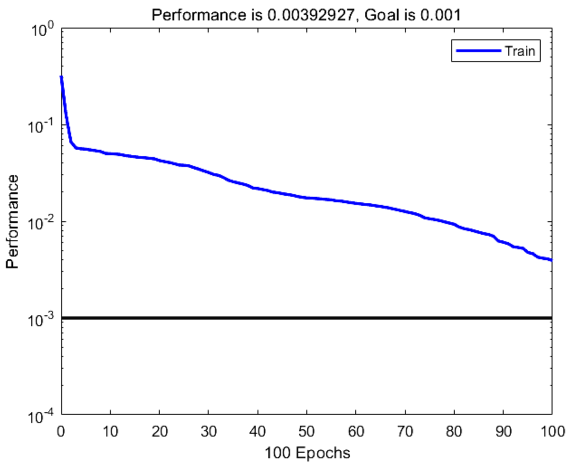


FIGURE 13. Convergence effect graph of RBF neural network.

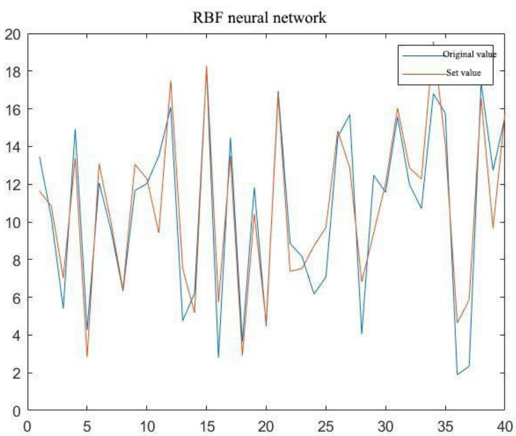


FIGURE 14. Fitting effect graph of RBF neural network.

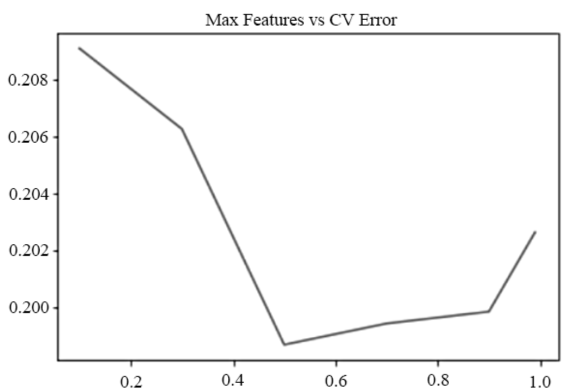


FIGURE 15. Fitting accuracy graph of XGBoost algorithm.

From the figure, the highest accuracy of the XGBoost prediction model is about 83%. From the analysis of the results, it can be seen that the combination of XGBoost's multiple weak classifiers to fit the sample data set does not have particularly high accuracy, and the XGBoost machine learning algorithm has high data requirements, the fitting performance for this small sample data set general. From this comparison, it can be seen that the training effect of the BP neural network on this sample data set and the performance effect on the test set are relatively excellent.

VI. MODEL OPTIMIZATION SOLUTION BASED ON GA ALGORITHM

GA algorithm [24] can quickly search for all solutions in the solution space without falling into local optimal solutions. Using the inherent parallelism of the GA algorithm, distributed calculations can be performed efficiently and the speed of the solution can be accelerated. It is difficult to solve some nonlinear, multi-objective, and multi-model function optimization problems with conventional optimization methods, but the GA algorithm can easily get better results. At present, the GA algorithm has been widely used in many fields, such as control engineering, deep learning, signal processing and so on. It is very suitable for the optimization of the noise prediction model of multi-stage gear modification of new energy vehicles.

Besides, the computational complexity and runtime of the algorithm must be considered. Algorithm complexity refers to the resources required by the algorithm to run after it is written into an executable program. Resources include time resources and memory resources. The execution time of the algorithm program can reflect the efficiency of the algorithm, that is, the pros and cons of the algorithm. The time complexity of the BP-GA method used in this article is $O(m \cdot n^2)$. The algorithm solving time is about half a minute. The overall performance is excellent.

The GA algorithm is used to solve the multi-stage gear vibration and noise prediction model. The objective function of the model is shown in (13), and the constraint condition of the parameter range is shown in (14):

$$a_{\min} = f(L_1, L_2, L_3, L_4, L_5, L_6) \tag{13}$$

$$s.t. \begin{cases} 0 \leq L_1 \leq 15 \\ -15 \leq L_2 \leq 15 \\ 0 \leq L_3 \leq 0.24 \\ 0 \leq L_4 \leq 17 \\ -17 \leq L_5 \leq 17 \\ 0 \leq L_6 \leq 12.4 \end{cases} \tag{14}$$

Here: $a_{\min}$ is the noise vibration acceleration (m/s^2); L_1 is the amount of first-stage gear tooth direction repair drum (μm); L_2 is the first-stage gear tooth inclination amount (μm); L_3 is the first-stage gear tooth profile modification amount(μm);L_4 is the amount of second-stage gear tooth direction repair drum (μm); L_5 is the second-stage gear tooth inclination amount (μm); L_6 is the second-stage gear tooth profile modification amount(μm).

The GA algorithm solves the prediction model, and the main process of achieving parameter optimization is as follows:

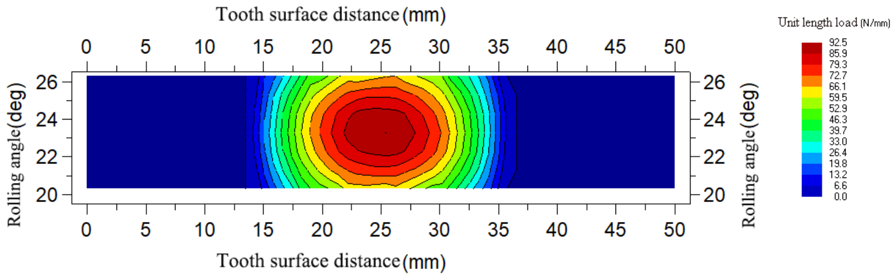


FIGURE 16. Unit load distribution of pinion 1 after optimized modification.

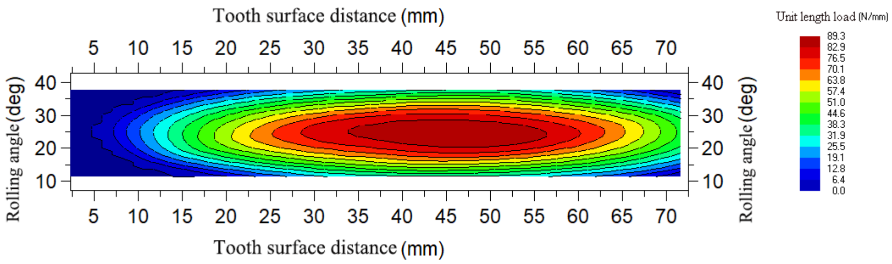


FIGURE 17. Unit load distribution of pinion 2 after optimized modification.

Select the initial population number to be 60, and the space dimension to be 6 dimensions; the maximum number of iterations is 50, the code length is 16, the crossover probability and mutation probability are 0.3 and 0.008 respectively; convert the gene (binary code) into the value of the independent variable (decimal number); normalize the corresponding decimal number and use the BP network to take the result as the value of the fitness function; the output result is unitized, roulette is played, and the optimal position is obtained.

The objective function of the model is the maximum vibration acceleration of noise generated by the new energy vehicle multi-stage gear transmission system under constant speed conditions. The constraint conditions of the model are the amount of the first-stage gear tooth direction repair drum, the first-stage gear tooth inclination, the first-stage gear tooth profile modification, the second-stage gear tooth direction repair drum, the second-stage gear tooth inclination, the second-stage gear tooth profile modification range. The GA algorithm is used to solve the prediction model, and the optimal solution of the combination of multi-stage gear modification parameters is obtained, as shown in Table 7:

TABLE 7. The optimal solution of multi-stage gear modification parameters combination.

	The first-stage gear modification amount	The second-stage gear modification amount
Tooth drum repair amount(μm)	14.8183	2.39095
Tooth inclination amount(μm)	4.438	-0.282763
Tooth profile modification amount(μm)	0.655964	2.41562
Maximum vibration acceleration (m/s^2)	1.9142	

VII. ANALYSIS OF THE EFFECT OF GEAR MODIFICATION OPTIMIZATION DESIGN

Import the optimal gear modification parameters obtained by solving the optimization model into Romax to establish a multi-stage reducer gear modification parametric model. Perform unit load analysis, transmission error analysis, and gear whistling noise analysis by the dynamic analysis process under constant velocity conditions. The two-stage gear transmission error corresponding to the optimal modification parameters is obtained, and the specific values are shown in Table 8. The load distribution per unit length of pinion 1 and pinion 2 is shown in Fig. 16 and Fig. 17. The simulation analysis results before and after the optimization modification are summarized, as shown in Table 9.

TABLE 8. Gear transmission linear error data after modification.

	First-stage gear set		Second-stage gear set	
	Rolling angle (deg): Pinion1	Displacement along the meshing line (μm)	Rolling angle (deg): Pinion2	Displacement along the meshing line (μm)
Maximum value	-68.95	7.36	-120.09	4.74
Minimum value	-125.87	7.28	-136.16	4.61
Range	56.92	8.27e-2	16.07	0.133

It can be seen from Table 7 and Table 9 that there is only a 5.7% error between the optimal vibration and noise

TABLE 9. Comparison table of simulation analysis data before and after modification under constant velocity conditions.

	Transmission error (μm)			Maximum noise vibration acceleration (m/s^2)			
	First-stage gear set	Second-stage gear set	Unit load distribution	Node 1	Node 3	Node 5	Node 8
Before modification	0.181	0.210	Severely biased	9.31	3.045	0.58	0.516
After optimal modification	0.0827	0.133	Evenly distributed	2.03	1.922	0.463	0.226

prediction value of node 1 obtained by solving the model of $1.9142 m/s^2$ and the actual simulation value of $2.03 m/s^2$ obtained by importing the optimal modification parameters into the transmission system model. The reliability of the optimized BP neural network vibration and noise prediction model established in this research is verified.

Compared with before the modification, the transmission error of the first-stage gear pair of the multi-stage gear transmission system after the modification is reduced from $0.181\mu m$ to $0.0827\mu m$, which is a reduction of $0.0983\mu m$, which is about 54% lower than that before the modification; the second-stage gear pair is reduced from $0.210\mu m$ to $0.133\mu m$, which is a reduction of $0.077\mu m$, which is about 37% lower than before modification. The unit load distribution of the gear has been improved from a severely unbalanced load to a uniform distribution, changing the contact spot type of the gear pair to the normal contact type. The maximum vibration acceleration of node 1, which measures the magnitude of vibration and noise, is reduced from $9.31 m/s^2$ to $2.03 m/s^2$, a decrease of 78.2%; the maximum vibration acceleration of node 3 is reduced from $3.045 m/s^2$ to $1.922 m/s^2$, with a reduction of 36.9%; the maximum vibration acceleration of node 5 is reduced from $0.58 m/s^2$ to $0.463 m/s^2$, the reduction range is 20.2%; the maximum vibration acceleration of node 8 is reduced from $0.516 m/s^2$ to $0.226 m/s^2$, which is 56.2%. It can be seen from the results that the solved optimal modification parameters can effectively reduce the vibration and noise of the multi-stage gear transmission system.

VIII. CONCLUSION

The parameterized model of the multi-stage gear transmission system of the new energy vehicle was established through Romax software, and the comprehensive gear modification method of the tooth direction combined with the tooth profile was established, then the dynamic analysis was performed. Multiple sets of simulation data are obtained by simulating the modification model with different modification parameters, after optimizing the BP neural network, the mapping relationship between gear modification parameters and vibration acceleration is obtained, and the corresponding prediction model is established. And taking the minimum vibration acceleration as the goal, using the GA optimization algorithm to solve the model to obtain the optimal combination of multi-stage gear modification parameters. Found the optimization method of the gear modification of the reducer of the new energy vehicle under the constant speed condition. The difficulty of solving the optimal value due to too many parameters involved in the multi-stage gear modification process is solved. A scientific and reliable modification parameter-vibration acceleration prediction model is constructed, which provides ideas and basis for the research on vibration and noise reduction of multi-stage gears. The main conclusions are as follows:

(1) Under constant speed operation conditions, the multi-stage gear transmission system continues to be parametrically modeled under the Romax platform. Based on the gear modification theory and combined with the meshing characteristics of the gear pair of new energy vehicles, a comprehensive modification method of tooth orientation and tooth profile is determined, then conduct dynamic simulation analysis. The optimization goals of improving gear load distribution, reducing gear transmission error and vibration acceleration are determined.

(2) The optimal selection of network parameters combined with Bayesian regularized BP neural network is used to establish a modified-vibration and noise prediction model. 80% of the randomly selected data is used as the training set for the training of the BP neural network model, and the remaining 20% of data is used as the test set to verify the performance of the BP neural network prediction model. The prediction accuracy of the model on the training set reached 99.46%, and the model was verified with the test set, the prediction accuracy also reached 99.03%, which proved the prediction performance of the model, solved the overfitting problem. This model also lays the foundation for finding the optimal modification parameters.

(3) The GA optimization algorithm is adopted to reduce the vibration acceleration and improve the gear transmission performance as the optimization goal. The optimization solution obtains the optimal modification parameter combination. Compared with before the modification, the load distribution of the two-stage gear of the multi-stage gear transmission system has been improved from severe eccentric load to even distribution; the transmission error of the first-stage gear pair is reduced by about 54%, and the second-stage

gear pair is reduced by about 37%; the maximum vibration acceleration of node 1 is reduced from $9.31m/s^2$ to $2.03m/s^2$, which is 78.2%; the maximum vibration acceleration of node 3 is reduced from $3.045m/s^2$ to $1.922m/s^2$, which is 36.9%; the maximum vibration acceleration of node 5 is reduced from $0.58m/s^2$ to $0.463m/s^2$, the reduction range is 20.2%; the maximum vibration acceleration of node 8 is reduced from $0.516m/s^2$ to $0.226m/s^2$, which is 56.2%. The simulation results show that reasonable modification using the optimal modification parameters obtained by this method can effectively reduce the vibration and noise of the multi-stage gear transmission system, thus verifying the feasibility of the model and method proposed in this article. It solves the problem of huge data space for predictive model optimization to solve multiple input parameters.

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