

MODAL ANALYSIS AND STRUCTURAL OPTIMIZATION OF GEAR MESHING NOISE IN NEW ENERGY VEHICLES

KangZhe Si

School of Materials and Metallurgy, Liaoning University of Science and Technology, Anshan 114051, Liaoning, China.

Abstract: With the rapid development of new energy vehicles, the noise source of its power system has changed significantly, in which the gear mesh noise of the gearbox has a direct constraint on the NVH performance of the whole vehicle. In this paper, a new energy vehicle three-in-one motor in the 7500-9000rpm speed range of the obvious gear whistling problem to carry out research, through the analysis to determine its main noise source for the first gear pair. The study used SolidWorks software to establish a three-dimensional model of the first gear, and imported into ANSYS for finite element modal analysis, and also calculated the gear meshing frequency based on the formula $f=n*z/60$. The analysis results show that under 8000rpm, the gear meshing frequency is very close to the first-order intrinsic frequency of the structure, which is very easy to trigger structural resonance, resulting in a stepwise increase in the noise sound pressure level. In order to suppress this resonance phenomenon, an economical and direct structural optimization scheme is proposed in this paper: the number of weight-reducing holes in the gear body is reduced from 8 to 4 to enhance the structural stiffness of the spokes. The optimized simulation results show that the first-order modal frequency of the gear is increased to about 3000 Hz, which successfully avoids the excitation frequency under the main working speed, so that the noise source under the common working conditions is transformed into the wind noise and the tire noise, and the gear meshing noise is effectively masked. The study confirms that structural optimization by adjusting the number of weight-saving holes is an effective and economical way to suppress the resonance noise of the gears in new energy vehicles, which improves the dynamic performance while taking into account the lightweight design objective.

Keywords: New energy; Vehicle gear meshing; Modal analysis; Noise

1 INTRODUCTION

With the large-scale development of new energy vehicle industry, the noise, vibration and sound vibration roughness performance of vehicle driving comfort has become an important technical index for evaluating product quality and market competitiveness. Compared with traditional fuel models, pure electric vehicles lack the noise masking effect of the internal combustion engine itself, and the high-frequency whistling noise generated by the electric drive system is particularly significant, in which the electromagnetic whistling triggered by the gear meshing process has become a key factor restricting the NVH performance of the whole vehicle[1]. Studies have shown that the periodic dynamic excitation generated during the dynamic meshing process of the gear pair is the fundamental physical mechanism that induces the whistling noise, and the transmission error, as a core parameter that characterizes the time-varying stiffness of the gears, is able to effectively quantify the amplitude of the vibration excitation of the gear system, and is therefore widely recognized by the academic community as a key evaluation index for assessing the excitation strength of the gear transmission[2].

New energy vehicles and traditional fuel vehicles, compared with the former powertrain noise source has changed significantly, in which the noise at low and medium speeds mainly originates from the mechanical vibration of the powertrain (such as reduction gearbox whistling, motor humming, etc.), the noise in the colormap diagram, you can see the obvious gear mesh order (with the mesh gears and the gear ratio), in the vicinity of the main order may also appear modulation phenomenon. Gear train noise is essentially sound radiation generated by structural vibration. The core source of excitation comes from the dynamic characteristics of the gear meshing process. It is widely recognized that the time-varying meshing stiffness (TVMS) is the most important parametric excitation within a gear system[3]. As the core component of the transmission system, the mesh noise of the motor gearbox is a direct constraint on the NVH (noise, vibration and harshness) performance of the vehicle. The noise generation mechanism is not only caused by tooth impact vibration, contact stress fluctuation and manufacturing assembly tolerance, at the same time, it may be due to the intrinsic frequency of the system and the excitation frequency overlap resonance, resulting in a specific meshing order in the target speed band presents a significant acoustic pressure peaks, which makes the customer uncomfortable, which gear vibration is not only caused by external factors but also the existence of internal vibration, for example, changes in the torque and speed and the teeth mesh caused by the Vibration[4]. The problem can be partially mitigated by engine sound insulation and low-speed design in conventional fuel vehicles, but the high-frequency and high-speed characteristics of the motors in new energy vehicles exacerbate the problem. Therefore, it is of great significance to study new vibration and noise reduction technologies to improve the comfort of new energy vehicles.

2 THE STATUS OF RESEARCH

According to the previous research results, the energy distribution of noise is mainly concentrated in the gear mesh frequency region, when the mesh frequency coupled with the inherent frequency of the transmission system, the structural resonance effect will be triggered, resulting in a stepwise increase in the noise sound pressure level, this resonance phenomenon can be induced in the engine at full speed conditions, which can easily be detected by the driver and passengers[5]. In order to address this problem, the previous system proposed a number of noise reduction strategies to significantly improve the acoustic performance of the gear transmission system, of which Li Shaochun et al. proposed the use of polished grinding process to improve the noise generated by the gear vibration[6]; Sanchez et al. on the contact of the gear teeth under the action of the load was studied[7], demonstrating the effect of the macro-parameters of the gear teeth on the distribution of load and transmission error; Wang Zeng on the contact of the gear teeth under the action of the load, proving that the macro-parameters of the gear teeth on the distribution and transmission error[7]. Wang Zeng analyzed the vibration noise of the gearbox[8], and optimized the gearbox structure according to the vibration noise of the gearbox; Sun et al. carried out topology optimization of the structural damping[9], and found an effective damping treatment method, which can get a higher modal loss factor, and verified the numerical model of topology optimization through the test of the modal loss factor; and scholars optimized the topology optimization of the gears by optimizing the macroscopic geometrical parameters and microscopic parameters of the gears, which can be used for the transmission of the gears, and the topological model of the gears. There are also scholars who optimize the macro-geometric parameters and micro-geometric morphology of gears to improve the meshing characteristics and reduce the amplitude and volatility of transmission errors[10]. Based on the parametric design method, this study focuses on the correlation mechanism between the modal characteristics of gears and the meshing noise, and focuses on the influence of the intrinsic vibration modes of gears on the meshing impact noise.

3 GEAR MODELING

This paper is based on the study of a new energy vehicle's three-in-one motor, found that the motor in the test process there is gear whistling, in the order diagram of the motor speed 7500 to 9000rpm at the peak of the noise is obvious, the order diagram is shown in Figure 1. The motor speed of the motor is about 1,000rpm, and the motor speed is about 2,000rpm, and the motor speed is about 2,000rpm.

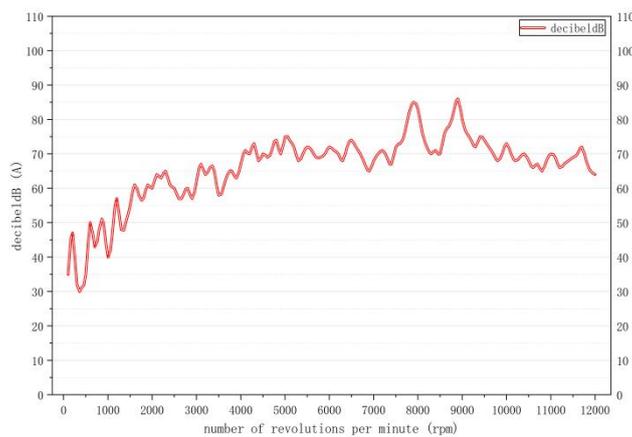


Figure 1 Overall Level

Now the product is analyzed, the name of each part is shown in Figure 2, the parameters of the motor is 4 pairs of poles and 48 slots, the gearbox is a 2-stage reduction, the maximum speed of 16,000 rpm, the number of teeth are 22 teeth 83 teeth 20 teeth 81 teeth[11]. After the study found that the cause mainly occurs in the first large gear, now set the parameters of the first large gear, the specific parameters as shown in Table 1.

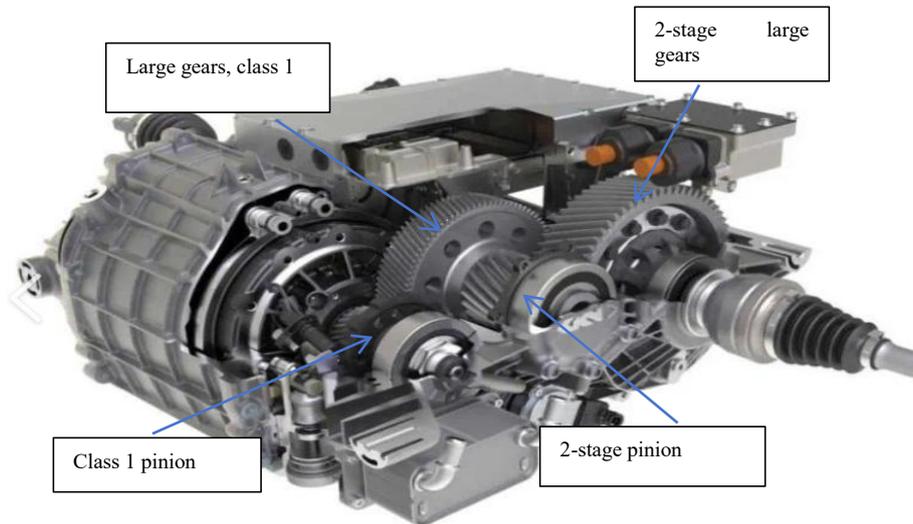


Figure 2 Schematic Diagram of the Motor

Table 1 Main Geometrical Parameters of the First Stage of the Large Gear

geometric parameters	Large gears, class 1
Module m/mm	2
Number of teeth z	83
pressure angle/(°)	20
Helix angle/(°)	22
Tooth width b/mm	35
Rotation	right

After completing the determination of macro-parameters of the first large gear, the gear is modeled using solidworks software, and the model is set to x_t format after the completion of the model, imported into ANSYS, set the material properties, mesh division, load and constraints, and finally perform model solving. The three-dimensional model of the first stage large gear is shown in Figure 3.



Figure 3 Gear Model

4 MODAL ANALYSIS OF GEAR MODELS

4.1 Establish the Finite Element Model of the Gear

The saved x_t 3D gear model is imported into ANSYS, and new material properties are set, including modulus of elasticity, density, Poisson's ratio, etc. The mesh is automatically meshed, and the tooth surface of the gear is encrypted, and the results are as accurate as possible. Mesh selection of automatic meshing method, the gear tooth surface encryption, try to accurate results, the structure of the finite element model shown in Figure 4.



Figure 4 Finite Element Model

4.2 Gear Modal Analysis

ANSYS modal analysis belongs to the category of linear analysis, and its calculation process ignores all nonlinear factors such as contact units and plastic deformation. The analysis process mainly includes the key steps of load application, extended modal solving and result analysis. In the specific implementation, firstly, set the analysis type as modal analysis in the solver and configure the relevant parameters, and then constrain the hole surface of the gear center shaft as a fixed support, and set the sixth-order modal expansion parameters at the same time. Through the above operations, a list of 6th order extended modal frequencies of the gear mechanism is finally obtained as shown in Table 2.

Table 2 Table of Modal Frequencies for the First 6 Orders

order	Frequency
1	2858.4
2	3056.8
3	3129.2
4	3498.8
5	3725.6
6	4126.5

The first 6 orders of vibration pattern of the gear mechanism are shown in Figure 5:



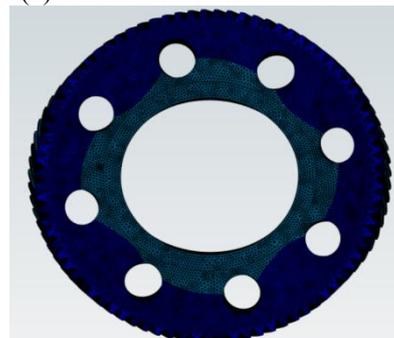
(a) First-order vibrational mode



(b) second-order vibrational mode



(c) Third-order vibrational mode



(d) Fourth-order vibrational mode

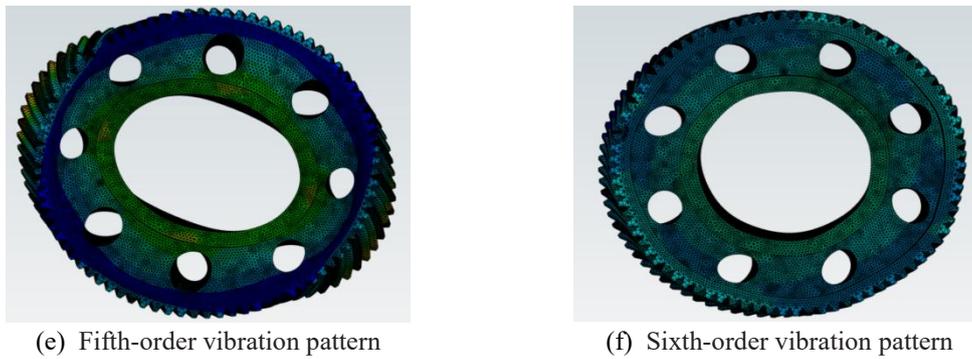


Figure 5 Schematic Diagram of the First Six Orders of Vibration

4.3 Modal Results and Analysis

Through the finite element modal analysis, the first six orders of intrinsic frequencies and corresponding intrinsic shapes of the gear structure are obtained. The first six orders of the solid frequencies and the corresponding solid vibration patterns are obtained through the finite element modal analysis. The first order solid frequencies listed in the table correspond to the specific modal vibration patterns, and the main vibration patterns of each order can intuitively reflect the displacement distribution characteristics of each node of the gear structure, and at the same time can be dynamically demonstrated by the animation function of the post-processing module, of which the first-order modes are mainly characterized by transverse bending vibration (left and right), the second-order modes show longitudinal bending vibration (up and down), the third-order modes are dominated by torsional vibration (left and right) and the fourth-order and fifth-order modes involve axial vibration (right and wrong). torsion), fourth-order and fifth-order modes involve axial vibration (front and back direction) and its combination, and the sixth-order modes show the breathing vibration mode of the whole structure. The gear meshing frequency is determined by the rotational speed and the number of teeth, and the formula is $f=n \times z / 60$, where n is the rotational speed of the gear in rpm, and z is the number of teeth of the gear. According to the formula, the frequency of the gear meshing at a rotational speed of 8,000 rpm is 2,933.33Hz, which is the closest to the first-order intrinsic frequency, and therefore the modes in this order can be stimulated by the meshing excitation most easily.

5 THEORETICAL VALUE CALCULATION

During motor operation, if the gear meshing frequency coincides with the structural modes, resonance will be triggered, leading to a sharp increase in noise at a specific speed. Therefore, it is necessary to calculate the gear meshing frequency at different speeds to identify the potential resonance risk. In this case, the frequency of the gear mesh at different rotational speeds is calculated.

The engagement frequency is calculated using the following formula:

$$f = \frac{n * z}{60} \quad (1)$$

Where, n is the gear speed, z is the number of gear teeth.

According to the above formula, the meshing frequency is 2933.33 Hz when the rotational speed is 8000 rpm, because this frequency is the closest to the first-order intrinsic frequency of the gears, so the modes of this order are very easy to be excited by the meshing excitation, which causes a sudden change in the vibration noise. In addition to the resonance point prediction, the analysis of the meshing frequency also has the following engineering significance: it is a characteristic mark in the vibration spectrum, the fundamental frequency component reflects the fluctuation of tooth load, the higher order harmonics often point to the machining error, and the sideband frequency can assist in the diagnosis of assembly faults. The vibration amplitude of the meshing order is directly related to the dynamic meshing stiffness change of the gear, which provides load input for strength check and fatigue life analysis. After clarifying the problem order, targeted measures such as helix angle optimization and tooth shape modification can be taken to effectively suppress the order noise.

6 OPTIMIZING GEAR MODELS

During low-speed operation, the inherent modes of the gears are easily excited by the meshing excitation, resulting in significant noise peaks, which seriously affects the NVH (Noise, Vibration, and Harshness) performance of the vehicle. In order to suppress this phenomenon, the dynamic characteristics of the gear system need to be optimized. Currently, the commonly used optimization methods include adjusting the number of teeth[12], replacing the material[13], or shaping the tooth profile[14], etc. However, these improvement measures are still subject to the constraints of significant increase in the manufacturing cost or complexity of the machining process in practical applications, and it is a more direct and economical way to improve the stiffness of the gears by altering the gear structural design.

In this paper, a structural optimization scheme is proposed to reduce the number of weight-reducing holes in the gear body from 8 to 4, and the optimized structure is shown in Figure 6. The design aims to enhance the structural stiffness of the spokes to avoid the occurrence of the first-order bending mode in the low-frequency band, so as to avoid the resonance noise induced by this mode fundamentally. The simulation results based on the optimized model are shown in Table 3, and the dynamic performance is significantly improved.



Figure 6 Modified Finite Element Model

Table 3 Modal Frequency Table for the First 6 Orders of the Modified

modal order	Frequency
1	3262.7
2	3374.8
3	3629.6
4	3794.6
5	4142.3
6	4451.9

By optimizing the gear structure, the first-order modal frequency is increased to about 3000 Hz, and under this condition, the main noise sources perceived by the driver inside the vehicle under the main working conditions where the gear mesh noise is excited (corresponding to a motor speed of about 8500 r/min and a vehicle speed of 80 km/h or more) are changed to the wind noise and the tire noise, and the gear mesh noise is effectively masked. In order to further investigate the influence of structural parameters, this study carries out a series of simulation verification on the number of weight-reducing holes. Firstly, the gear model with 6 weight reduction holes and the two models with 4 weight reduction holes are selected for detailed analysis, and the first six modal vibration patterns are shown in Figure 8, and the model diagram is shown in Figure 7, and the corresponding intrinsic frequency values are listed in Table 4. The modal characteristics of the four-hole and six-hole structures are compared, and the results of different types of models are shown in Table 5, with the increasing number of weight-reducing holes, the modal frequency of the gear structure is gradually reduced. In order to avoid the resonance of the modal frequency of the gear system with the meshing order, it is recommended to choose the structural scheme with 4 holes for weight reduction by comprehensive data analysis.

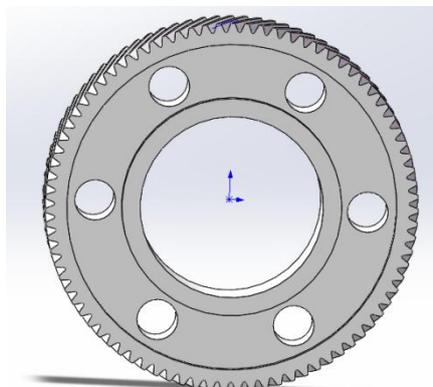


Figure 7 Model Diagram for Weight Reduction Hole of 6

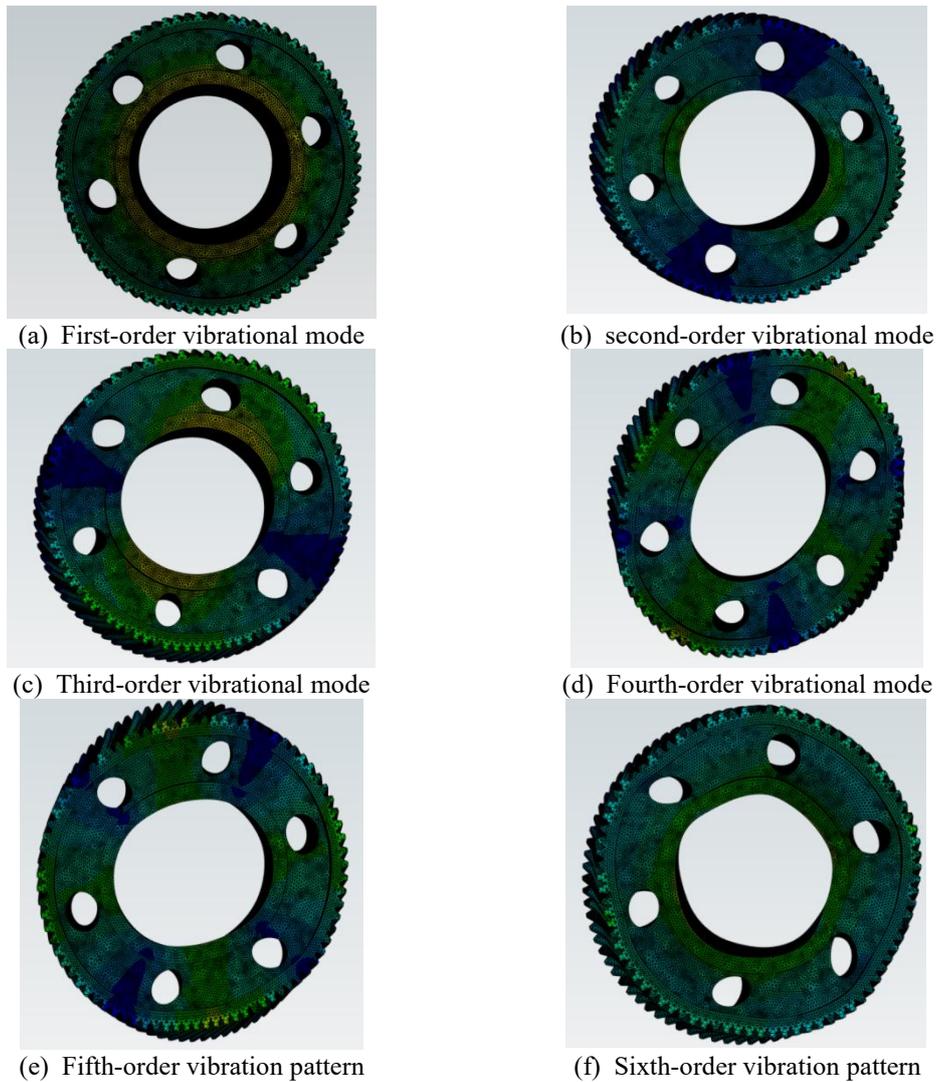


Figure 8 The First Six Orders of Vibration Patterns for a Weight-Loss Hole of 6

Table 4 The First Six Orders of Modes

modal order	Frequency
1	2986.4
2	3184.3
3	3426.5
4	3521.7
5	3958.4
6	4234.5

Table 5 Comparison of the Frequencies of the Programs

modal order	The frequency at which the weight-reducing holes are 8	weight loss holes for a frequency of 6	weight loss holes for a frequency of 4
1	2858.4	2986.4	3262.7
2	3056.8	3184.3	3374.8
3	3129.2	3426.5	3629.6
4	3498.8	3521.7	3794.6
5	3725.6	3958.4	4142.3
6	4126.5	4234.5	4451.9

7 CONCLUSION

In order to improve the dynamic performance of the gearing system and avoid the resonance under specific working conditions, this paper carries out a study on the typical working condition of 8000 r/min rated speed. Firstly, the meshing frequency of the gears at this speed is defined as the key excitation frequency to evaluate the resonance risk. In order to systematically analyze the influence of weight-reducing holes on the modal characteristics of gears, this study establishes a number of gear models based on the finite element method, corresponding to different configurations

of weight-reducing holes. Through the modal analysis, the modal parameters such as the intrinsic frequency and vibration pattern of each model were obtained. The results are summarized in the following table. The analysis results show that when the number of weight reduction holes is 6 or more, the first-order intrinsic frequency of the gear is too close to the meshing excitation frequency at 8000 r/min, and there is a significant risk of resonance. Based on the principles of vibration suppression and structural optimization, the 4-hole weight reduction scheme is finally adopted after weighing the dynamic performance and lightweighting requirements. This scheme effectively improves the intrinsic frequency of the gear, successfully avoids the excitation frequency under the main working speed, and realizes the optimal balance between dynamic stability and lightweight target.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

REFERENCES

- [1] Owen J Harris, Paul P Langlois, Cooper G A. Noise Reduction in an EV Hub Drive Using a Full Test and Simulation Methodology. *Gear technology*, 2016, 33(3): 44-53.
- [2] Palermo A, Britte L, Janssens K, et al. The measurement of Gear Transmission Error as an NVH indicator: Theoretical discussion and industrial application via low-cost digital encoders to an all-electric vehicle gearbox. *Mechanical Systems and Signal Processing*, 2018: 110368-389. DOI: 10.1016/j.ymssp.2018.03.005.
- [3] Kong Y, Jiang H, Dong N, et al. Analysis of Time-Varying Mesh Stiffness and Dynamic Response of Gear Transmission System with Pitting and Cracking Coupling Faults. *Machines*, 2023, 11(4): 500-. DOI: 10.3390/machines11040500.
- [4] Jingrui Y, Yihe Z, Hee C L. Multi-parameter optimization-based design of lightweight vibration-reduction gear bodies. *Journal of Mechanical Science and Technology*, 2022, 36(4): 1879-1887. DOI: 10.1007/s12206-022-0325-1.
- [5] Liu W, Zhu X, Gao T, et al. Static and dynamic characteristic analysis and multi-objective topology optimization of gearbox body. *Mechanical Strength*, 2025, 47(2): 94-102. DOI: 10.16579/j.issn.1001.9669.2025.02.012.
- [6] Li S, Chu Y, Yu Z, et al. Experimental analysis of the effect of polishing and grinding process on gear vibration noise. *Mechanical Transmission*, 2020, 44(8): 137-141. DOI: 10.16578/j.issn.1004.2539.2020.08.024.
- [7] Tang H, Zhao X, Zhang J, et al. Analysis and optimization of transmission gears for new energy vehicles. *Journal of Chongqing University of Technology (Natural Science)*, 2025, 39(1): 177-184.
- [8] Ni J. Characterization of vibration-noise coupling of bogie gearboxes in metro vehicles. *Mechanical Transmission*, 2023, 47(12): 123-130. DOI: 10.16578/j.issn.1004.2539.2023.12.018.
- [9] You Y, Cao X. Analysis of the effect of load transmission error on vibration characteristics of curved bevel gears based on MASTA simulation. *Mechanical Transmission*, 2021, 45(9): 56-61, 67. DOI: 10.16578/j.issn.1004.2539.2021.09.008.
- [10] Kohn B, Fromberger M, Weinberger U, et al. Design of Low Noise Micro Geometries for Helical Gears on the Basis of Transmission Error Under Load. *Curran Associates, Inc.*, 2017: 2938-2945.
- [11] Tang Z, Tu S, Wang M, et al. Dynamic characterization of secondary reduction gearbox transmission system for new energy vehicles under multiple working conditions. *Journal of Chongqing University of Technology (Natural Science)*, 2022, 36(8): 75-85.
- [12] Kong Y, Jiang H, Dong N, et al. Analysis of Time-Varying Mesh Stiffness and Dynamic Response of Gear Transmission System with Pitting and Cracking Coupling Faults. *Machines*, 2023, 11(4): 500-. DOI: 10.3390/machines11040500.
- [13] Pang F, Dai Z. Improvement of engine belt timing system engagement noise discussion. *Internal Combustion Engines and Accessories*, 2024(18): 69-71. DOI: 10.19475/j.cnki.issn1674-957x.2024.18.022.
- [14] Palermo A, Britte L, Janssens K, et al. The measurement of Gear Transmission Error as an NVH indicator: Theoretical discussion and industrial application via low-cost digital encoders to an all-electric vehicle gearbox. *Mechanical Systems and Signal Processing*, 2018, 110368-389. DOI: 10.1016/j.ymssp.2018.03.005.