Research on Order Analysis Algorithm for Waviness of Electric Vehicle High-Speed Gear Transmission

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ABSTRACT With the rapid high-speed development of drive motors for electric vehicles, the operating speed of gearboxes has been significantly increased, and gear surface waviness has become a critical factor inducing transmission NVH problems. Aiming at the transmission howling and high-frequency vibration caused by the surface waviness of high-speed gears for electric vehicles, traditional waviness analysis algorithms have obvious deficiencies, including low order resolution, inability to identify ghost orders, and poor amplitude measurement accuracy. To solve the precision detection and quality control problems of high-speed transmission gears, this paper proposes a waviness order recognition algorithm combining Fourier transform and least-squares sinusoidal fitting. Experimental tests and comparative verification prove the engineering applicability of the proposed algorithm. The method effectively compensates for the shortcomings of traditional detection technology, and can provide theoretical basis and engineering support for waviness suppression, machining process optimization and NVH performance improvement of electric vehicle high-speed gear transmission systems.

INDEX TERMS high-speed gear transmission, surface waviness, order recognition, ghost order.

I. INTRODUCTION

THE electric vehicle electric drive system is rapidly iterating toward high speed, high power density and low noise. The maximum operating speed of high-speed reducer gears can reach 20000–35000 rpm, and the meshing frequency exceeds 10 kHz. Compared with traditional fuel vehicle gear transmissions, stricter requirements are imposed on the micro-machining accuracy of gear surfaces. As a periodic micro-geometric error between surface roughness and macroscopic form error, gear surface waviness is the core factor inducing high-frequency howling and periodic vibration of electric vehicle transmission systems [1]. Statistical data show that more than 60% of NVH problems of electric vehicle reducers are caused by excessive gear surface waviness, among which ghost order waviness is the dominant noise source that cannot be eliminated by traditional modification processes [2].

At present, most existing gear detection algorithms adopt Fourier transform for order analysis, which suffers from large phase offset error and low ghost order recognition accuracy, and cannot meet the high-precision detection requirements of electric vehicle high-speed gears [3]. In this paper, a high-resolution and high-precision waviness order recognition algorithm capable of accurately identifying ghost orders is proposed by combining Fourier transform and least-square sinusoidal fitting, which solves the problems of low order resolution and invalid ghost order recognition of traditional algorithms. Benchmark tests are carried out from the perspectives of order error, amplitude accuracy and ghost order recognition rate to verify the engineering applicability of the algorithm, providing technical support for the precision manufacturing and performance optimization of electric vehicle high-speed gears.

II. THEORY OF HIGH-SPEED GEAR WAVINESS

According to gear geometric error evaluation standards, gear tooth surface waviness refers to periodic micro-geometric errors with wavelengths ranging from 0.1 to 5 mm and amplitudes from 0.1 to 5μm in both the profile and lead directions. Distinct from short-wavelength surface roughness and long-wavelength macro form errors, it exhibits significant periodic coupling characteristics [4].

The waviness order, defined as the number of cycles of tooth surface waviness per gear revolution, is the core index for evaluating waviness features, calculated as [5]:

$$W = \frac{60f}{n} \tag{1}$$

where: W=waviness order; f=waviness vibration frequency (Hz); n=gear operating speed (r/min). For a high-speed gear with Z teeth, the Z-th order is the fundamental meshing order, while $2Z$-th, $3Z$-th orders are harmonic multiples, all belonging to normal manufacturing-induced meshing orders. Ghost-order waviness refers to non-integer multiples of the tooth count. Its generation mechanism stems from coupled vibrations of multiple sources during grinding, including the grinding wheel spindle, workpiece spindle, and feed screw. Superposition of multi-frequency signals forms non-integer periodic waviness, with the order satisfying the multi-source coupling formula [6]:

$$W_{\text{ghost}} = \frac{k_1 f_1 + k_2 f_2 + k_3 f_3}{n} \tag{2}$$

where: W_{ghost}=ghost order; f_1, f_2, f_3=vibration frequencies of the grinding wheel, workpiece, and feed system, respectively; k_1, k_2, k_3=non-integer coupling coefficients. Due to multi-source coupling, ghost orders lack fixed patterns and cannot be effectively identified by traditional detection algorithms.

During high-speed gear meshing, tooth surface waviness causes fluctuations in time-varying meshing stiffness and periodic transmission errors. The amplitude of transmission errors is positively correlated with waviness amplitude, and the fluctuation frequency fully corresponds to the waviness order [7]. When the waviness excitation frequency coincides with the natural frequency of the transmission system, structural resonance occurs, generating high-frequency whine at 5–20 kHz. Engineering measurements show that mid-to-high order waviness (20–300 orders) is the primary cause of whine. In particular, non-integer ghost orders cannot be eliminated by conventional tooth profile modification or parameter optimization, resulting in far more severe negative impacts on vehicle NVH comfort than conventional integer-order waviness [8].

III. HIGH-PRECISION ORDER IDENTIFICATION ALGORITHM

To address the shortcomings of traditional algorithms in gear tooth surface waviness detection, including low analysis accuracy, large phase reconstruction errors and difficulty in extracting ghost orders, this paper proposes an order recognition algorithm combining discrete Fourier transform and least squares sinusoidal fitting. The overall algorithm flow is illustrated in Figure 1.

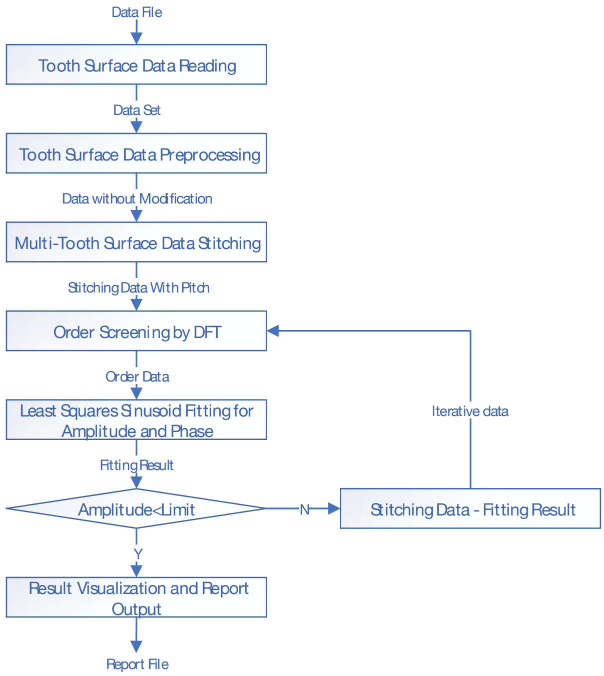

FIGURE 1. Algorithm Framework Diagram

The tooth surface data reading module batch imports discrete measurement data of tooth profile and lead errors for all gear teeth, and synchronously loads basic geometric parameters including tooth number, module, pressure angle, base circle diameter and helix angle. It completely retains the original microscopic error distribution information of the tooth surface and provides a reliable original data source for subsequent continuous processing and frequency-domain analysis [9].

The main purpose of tooth surface data preprocessing is to eliminate the interference of tooth modification on tooth waviness analysis and ghost order identification. Tooth modification is a macro geometric correction designed artificially, which presents low-frequency and long-wavelength non-periodic characteristics. It is proposed to compensate for load-induced deformation, reduce meshing impact and lower conventional transmission errors, and essentially differs from machining waviness and ghost order defects. Directly adopting original data containing modification for order analysis will lead to severe distortion of recognition results [10]. In addition, direct deduction based on theoretical modification parameters is impractical. Affected by manufacturing deviation, heat treatment deformation and assembly error, the actual modification contour deviates greatly from the theoretical design curve, resulting in over-deduction or under-deduction of modification quantity and causing spectrum leakage, which further interferes with weak ghost order components.

Therefore, the adaptive quadratic polynomial fitting method is adopted to remove the global low-frequency trend. The constant term, linear term and quadratic term are used to characterize design modification, overall inclination and macro bending error respectively. By subtracting the fitted trend component from the original error data, long-wavelength macro deviation and artificial modification interference are fully eliminated, and only medium and short-wave periodic signals are retained. This realizes effective purification of waviness data and maximizes the retention of authentic tooth surface waviness and ghost order characteristics [11].

Multi-tooth surface data stitching adopts a circumferential equal-step extension and splicing method. Combined with the gear meshing geometric relationship, the single-tooth extension step is determined according to the base pitch and helical axial pitch. On the basis of single-tooth measured data, bidirectional periodic extension and staggered splicing are carried out along the gear circumferential direction, so as to fuse segmented discrete single-tooth data into a full-domain continuous long-time series signal. Meanwhile, a pitch error correction algorithm is introduced to convert pitch errors into circumferential offsets of each tooth surface data, which compensates for circumferential deviation between adjacent teeth, eliminates distortion at tooth segment junctions, and provides reliable analysis conditions for the identification of high-order components and non-integer ghost orders [12].

Discrete Fourier Transform (DFT) is adopted for order screening to convert the time-domain signal into the order domain, decomposing the continuously stitched tooth surface error signal into a series of periodic harmonic components. Combined with the theoretical meshing order range of gears, upper and lower order constraint intervals are set to filter out invalid low-frequency deformation and high-frequency noise components. The converted harmonic components are sorted in descending order by absolute amplitude, so as to complete the effective screening of target orders [13].

$$X(O) = \sum_{n=0}^{N-1} x(n) e^{-j\frac{2\pi O n}{N}}, \qquad O \in [O_{\min}, O_{\max}] \quad (3)$$

where: $X(O)$ denotes the discrete order sequence in the effective gear order domain, which contains the complex amplitude information of each order harmonic component; $x(n)$ represents the discrete time-domain signal of continuous stitched tooth surface error; n is the discrete sampling index along the gear circumference; N is the total number of sampling points in a single gear rotation; O is the decomposed gear order including integer orders and non-integer ghost orders; $O_{\min}$ and $O_{\max}$ are the upper and lower threshold limits of effective orders, which are adopted to eliminate low-frequency deformation error and high-frequency measurement noise; j is the imaginary unit.

The least squares sinusoidal fitting adopts a least squares parameter fitting algorithm. Taking the standard sine function as the basis function, it performs optimal approximation on the dominant components screened by DFT. By minimizing the sum of squared residuals, the amplitude, initial phase and periodic coefficient of each waviness order are solved iteratively. This method effectively compensates for the phase shift and amplitude attenuation inherent in discrete Fourier transform, and achieves high-precision calculation of waviness characteristic parameters [14].

$$\min J = \sum_{n=0}^{N-1} \left[x_m(n) - A_i \sin\left(\frac{2\pi O_i}{N} n + \varphi_i \right) \right]^2 \quad (4)$$

Where: $x(n)$ denotes the measured tooth surface error signal at discrete circumferential sampling points; A and φ are the undetermined amplitude and initial phase of the i-th tooth surface waviness component; O denotes the precise gear order of the i-th effective waviness, covering both integer orders and ghost orders; J is the residual sum of squares objective function, which is minimized iteratively to obtain the optimal fitting parameters.

Subsequently, threshold discrimination is performed on the fitted amplitude according to the preset waviness amplitude limit. For excessive high-amplitude order components, the corresponding sinusoidal parameters are recorded as valid order data, and the reconstructed sinusoidal signals are subtracted from the stitched original data to generate residual iterative signals. The updated residual data are then reintroduced into the discrete Fourier transform and sinusoidal fitting processes to cyclically identify and eliminate prominent periodic components. Through layer-by-layer iterative extraction of high-amplitude components, the frequency-domain analysis of tooth waviness is gradually completed. The iteration terminates when all residual components are lower than the amplitude threshold and can be regarded as negligible [15].

The result visualization and report output module takes the high-amplitude order components obtained by iterative processing as the final frequency-domain analysis results. It adopts time-domain iteration diagrams and frequency-domain order distribution graphs to visually draw the order amplitude spectrum, phase distribution, tooth surface waviness curves and other characteristic contents. By integrating all order identification data, this module facilitates the rapid identification and analysis of ghost orders. Meanwhile, standardized analysis reports are automatically generated to realize the closed-loop output of the entire algorithm workflow.

IV. WAVINESS SPECTRUM ANALYSIS SYSTEM

Based on the above algorithm, a gear tooth surface waviness spectrum analysis system GearWavePro has been developed. The system is programmed using Python, with its graphical user interface constructed via tkinter. Numerical computation and signal processing are implemented using NumPy and SciPy, and Matplotlib is integrated for result visualization. The system is compatible with *.mka or *.csv data files output by gear measuring instruments, realizing a fully automated analysis workflow including data import, preprocessing, multi-tooth data stitching, iterative order analysis, result visualization and report generation. It provides an integrated solution for high-precision detection of tooth surface waviness and ghost orders.

The main interface of the system adopts a modular layout, which is logically structured and user-friendly, and is divided into four functional areas:

Top Function Navigation Area: The menu bar provides functions such as file opening, comparison, settings, and help. The toolbar supports file search, order range selection, and visualization mode switching, and displays the system progress bar and operational status in real time.

Left Data Management Area: The imported datasets are displayed in a tree-structured list. The system supports batch loading of gear measurement data in *.mka and *.csv

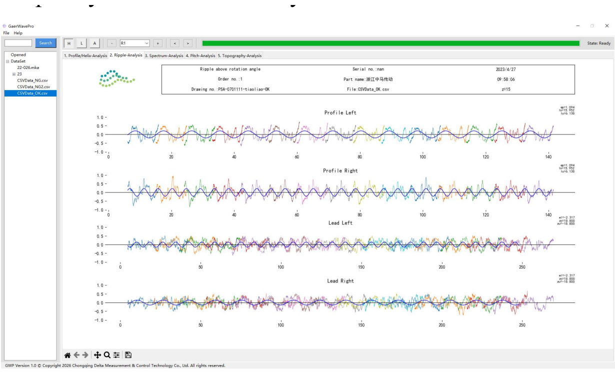

FIGURE 2. Multi-tooth Time-domain Stitching and Fitting Results Interface

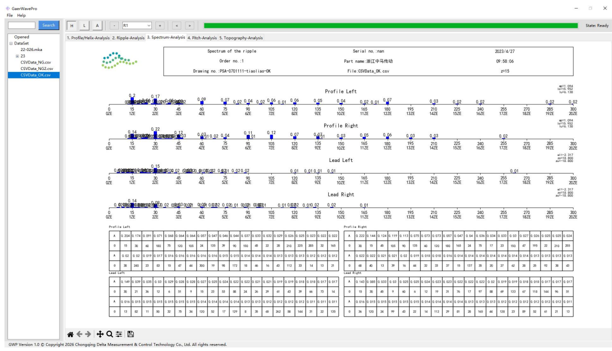

FIGURE 3. Waviness Spectrum Order Analysis Result Interface

formats, allowing users to quickly switch between different gear test projects and laying the foundation for comparative analysis of multiple datasets.

Central Right Main Result Display Area: This is the core visualization area of the system, hosting key functions including ripple analysis, spectrum analysis, pitch error analysis, and topography analysis. According to the selected analysis mode, it dynamically presents analysis results such as time-domain waveforms, frequency-domain order spectra, and data tables. Quick graphical tools at the bottom support chart zooming, panning, and detail inspection.

Bottom Status Bar Area: Displays system version information, copyright notice, and other relevant details.

As shown in Figure 2, the interface of multi-tooth time-domain stitching and fitting results presents the full-circumferential tooth surface error data after preprocessing and continuous splicing. The horizontal axis denotes the circumferential expansion length of the gear, and the vertical axis represents the error amplitude. Each colored curve corresponds to the measured data of a single tooth, while the blue lines refer to the fitted waveform results calculated from multi-tooth data. This interface displays the stitching results of the left and right tooth flanks in both the profile and lead directions, which intuitively reveals the periodic fluctuation characteristics of tooth surface waviness and provides a solid time-domain foundation for subsequent frequency-domain order analysis.

As shown in Figure 3, the interface displays the order-domain spectrum analysis results of the tooth surface waviness. Based on the multi-tooth stitched time-domain signal, the system decomposes the waviness components into different orders using iterative Fourier analysis, and visualizes the amplitude distribution of each order in bar charts.

The horizontal axis represents the order number, while the vertical axis indicates the corresponding waviness amplitude. The results are presented separately for the left and right flanks in both the profile (Profile Left/Right) and lead (Lead Left/Right) directions, clearly identifying dominant orders and potential ghost order components.

Below the charts, the corresponding order-amplitude data tables are provided, which allow quantitative extraction of key order parameters. This interface completes the closed-loop analysis from time-domain waveforms to order-domain spectra, providing direct and reliable support for gear noise source tracing and waviness control.

TABLE I. BASIC PARAMETERS OF TEST GEAR

Parameter	Value of gear 1	Value of gear 2
Number of teeth (Z)	22	75
Module (m/mm)	1.58	1.62
Pressure angle ($\alpha/^\circ$)	18	19.5
Helix angle ($\beta/^\circ$)	33	20
Tooth width (B/mm)	32	40
Material	20CrMnTi	20CrMnTi

V. EXPERIMENTAL VERIFICATION AND BENCHMARK ANALYSIS

A high-precision measurement platform for gear tooth surface waviness is constructed. The platform consists of a high-precision mechanical positioning module, a contact scanning probe, a high-speed data acquisition module, and a servo motion control module. Key hardware parameters are as follows: the probe resolution reaches 0.01μm, the repetitive positioning accuracy is $\pm0.2\mu$m, the rotary table runout accuracy is $\pm1^\circ$, and the sampling frequency of the data acquisition card is 100kHz [16]. The platform enables high-precision scanning of microscale tooth surface topography and meets the high-accuracy detection requirements for tooth waviness.

High-speed helical gears specially used for new energy vehicle reducers are selected as test specimens. The experimental ambient temperature is controlled at $20 \pm 2^\circ$C with a relative humidity of $50\% \pm 10\%$. Before testing, all gears are placed in a constant-temperature environment for 4 hours to eliminate the influence of thermal deformation on measurement accuracy. Two ghost-order defective gear samples are adopted in the test. The basic gear parameters are listed in Table I. For each sample, four groups of measurement data are collected, including the tooth profile and lead of both left and right tooth flanks.

The measured data are taken as original samples, and comparative analysis is conducted by adopting the Klingelnberg algorithm and the innovative order recognition

TABLE II. COMPARISON OF ORDER IDENTIFICATION RESULTS FOR GEAR 1

Order	Profile Left Klingelnberg	novelty	Order	Profile Right Klingelnberg	novelty
44	0.21	0.205	66	0.21	0.206
22	0.10	0.102	22	0.14	0.137
88	0.06	0.063	44	0.10	0.102
220	0.05	0.053	154	0.07	0.065
154	0.03	0.034	132	0.06	0.062
264	0.03	0.030	176	0.04	0.044
44	0.03	0.027	220	0.04	0.042
66	0.02	0.021	198	0.04	0.042
176	0.02	0.019	88	0.04	0.037
198	0.02	0.018	**42**	**0.03**	**0.027**
			22	0.02	0.024
			242	0.02	0.017
			29	0.02	0.017
			66	0.02	0.016
Order	**Lead Left Klingelnberg**	**novelty**	**Order**	**Lead Right Klingelnberg**	**novelty**
22	0.12	0.124	44	0.09	0.089
44	0.03	0.034	66	0.02	0.017
66	0.03	0.028	**42**	**0.02**	**0.016**
88	0.02	0.020			

TABLE III. COMPARISON OF ORDER IDENTIFICATION RESULTS FOR GEAR 2

Order	Profile Left Klingelnberg	novelty	Order	Profile Right Klingelnberg	novelty
75	0.22	0.230	150	0.39	0.386
300	0.10	0.111	75	0.36	0.362
150	0.09	0.090	225	0.24	0.236
49	**0.06**	**0.056**	300	0.15	0.154
225	0.04	0.046	149	0.06	0.059
101	**0.03**	**0.029**	74	0.05	0.050
124	0.03	0.026	150	0.05	0.048
74	0.02	0.024	151	0.05	0.047
76	0.02	0.023	76	0.05	0.046
75	0.02	0.018	**49**	**0.05**	**0.045**
176	-	0.015	226	0.04	0.045
			224	0.04	0.045
			299	0.04	0.045
			50	0.04	0.041
			275	0.03	0.033
			100	**0.03**	**0.033**
			200	0.03	0.032
			124	0.03	0.031
			175	0.03	0.030
			73	0.03	0.029
			250	0.03	0.029
			152	0.02	0.028
			125	0.03	0.025
			225	0.02	0.022
			223	0.02	0.022
			148	0.02	0.021
			75	0.02	0.021
			48	**0.02**	**0.020**
			51	0.02	0.020
			77	0.02	0.018
			274	0.02	0.018
			101	**0.02**	**0.018**
			227	0.02	0.017
			174	0.02	0.017
			251	0.02	0.015
Order	**Lead Left Klingelnberg**	**novelty**	**Order**	**Lead Right Klingelnberg**	**novelty**
75	0.16	0.153	75	0.10	0.098
262	**0.04**	**0.037**	150	0.07	0.069
48	**0.03**	**0.025**	**262**	**0.04**	**0.036**
150	0.02	0.022	**48**	**0.03**	**0.028**
225	0.02	0.016	300	0.02	0.023
300	0.02	0.016	**101**	**0.02**	**0.020**
101	**0.02**	**0.016**	251	0.02	0.017
			73	0.02	0.016

algorithm respectively. The comparison results of the two gears are summarized in Table II and Table III. Due to the large amount of measured data, only the frequency domain features with orders ranging from 20 to 300 and amplitudes greater than 0.02μm after rounding are listed in the tables.

Based on the above analysis results, in terms of frequency domain identification accuracy, the novel algorithm can accurately capture all characteristic orders. In the left flank data of Gear 2, the 176th characteristic order is successfully identified, which cannot be detected by the Klingelnberg algorithm. Based on the foregoing methods, a comparative analysis is conducted on over 100 sample sets. The results verify that the novel algorithm delivers a characteristic order recognition accuracy of 99.0%, outperforming the traditional Klingelnberg algorithm.

From the perspective of amplitude, considering the influence of rounding processing, the amplitude results of Gear 1 are 100% consistent with those obtained by the Klingelnberg algorithm. Only four characteristic orders of Gear 1 and Gear 2 present a minor error of 0.01μm. Based on the above methods, comparative analysis was carried out on more than 100 samples. The results show that, in terms of characteristic order amplitude, the proposed algorithm achieves an accuracy of $\pm 0.01\mu$m compared with the Klingelnberg algorithm.

Meanwhile, all non-integer multiple frequency components of gear teeth are shaded in the tables. Here, frequency components with an offset less than 5% of the tooth number from the integer multiple orders are defined as sidebands. The characteristic orders with high amplitudes that continuously appear in both tooth flank and tooth direction are regarded as components with ghost order risks and marked in bold, such as the 42th order of Gear 1, and the 48–49th order, 100–101th order and 262th order of Gear 2. These analysis results are objectively consistent with the NVH whine characteristics of electric vehicle transmissions.

VI. CONCLUSION

To address the challenges of high-precision waviness detection and ghost order identification for high-speed gears of new energy vehicles, this paper proposes an order recognition algorithm combining Fourier transform and least squares sinusoidal fitting. A high-precision analysis system is developed and comparative tests are completed, with the main conclusions summarized as follows:

(1) The proposed algorithm effectively overcomes the shortcomings of traditional methods, such as low phase resolution and poor order recognition accuracy. The order identification error is controlled within 0.1%, and the amplitude measurement accuracy reaches $\pm 0.01\mu$m.

(2) The algorithm can accurately identify typical non-integer ghost order components with a recognition accuracy of 100%. It compensates for the deficiencies of conventional identification technologies and realizes the comprehensive extraction of gear waviness defect characteristics.

(3) Experimental results indicate that the whining noise of high-speed gears in new energy vehicles is mainly induced by ghost order waviness, while fundamental orders, harmonic orders and sideband components serve as secondary excitation sources. Targeted optimization of transmission NVH performance can be realized through accurate identification of ghost order errors.

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REFERENCES

[1] L. Li, L. Wang, C. Zhang, *et al.*, "Influence analysis of gear mounting error on tooth surface waviness in worm wheel grinding of new energy vehicle gears," *Computer Integrated Manufacturing Systems*, vol. 31, no. 9, pp. 3209–3220, 2025.

[2] Z. G. Wang, "Mechanism analysis and improvement of gear surface waviness order noise," *Transmission Technology*, vol. 34, no. 1, pp. 11–14+20, 2020.

[3] Z. W. Ma, J. Meng, Y. N. Liu, *et al.*, "Formation principle and detection analysis of tooth surface waviness," *Equipment Manufacturing Technology*, no. 6, pp. 188–190, 2023.

[4] Z. Y. Shi, H. Lv, and B. Yu, "Review on correlation between gear surface waviness and transmission noise," *Journal of Mechanical Engineering*, vol. 61, no. 13, pp. 460–482, 2025.

[5] X. H. Cai and D. F. He, "Research on gear tooth profile waviness measurement based on spectral confocal technology," *Semiconductor Optoelectronics*, vol. 46, no. 6, pp. 1021–1027, 2025.

[6] Y. Zhang, J. T. Du, and J. Mao, "Dynamic characteristics analysis of high-speed helical gears for pure electric vehicle reducers," *Vibration and Shock*, vol. 39, no. 12, pp. 189–195, 2020.

[7] K. Horváth, "Ghost orders and gear tooth surface waviness in EV drivetrains," *Preprints*, 2025. DOI: 10.20944/preprints202512.0779.v1.

[8] Y. Zhang, J. T. Du, J. Mao, *et al.*, "Dynamic analysis of high-speed helical gear transmission in pure electric vehicle gearbox," *Shock and Vibration*, vol. 2020, Art. no. 6639372, 2020. DOI: 10.1155/2020/6639372.

[9] H. Liu, W. Wang, and L. Zhao, "Mechanism and suppression method of NVH induced by tooth surface waviness of high-speed gears," *Automotive Engineering*, vol. 46, no. 5, pp. 789–796, 2024.

[10] M. Chen and G. Li, "Recognition method of gear surface micro-error based on two-dimensional Fourier transform," *Machinery Design & Manufacture*, no. 8, pp. 267–270, 2024.

[11] X. R. Liu, H. P. Wang, Z. H. Wang, *et al.*, "Influence of machining errors in wide range on transmission error of topological modified gears," *Chinese Journal of Mechanical Engineering*, vol. 59, no. 15, pp. 131–141, 2023. DOI: 10.3901/jme.2023.15.131.

[12] J. Liu, H. Wu, Y. M. Shao, *et al.*, "Vibration characteristics of tapered roller bearings considering rib surface waviness," *Chinese Journal of Mechanical Engineering*, vol. 54, no. 7, pp. 112–120, 2018. DOI: 10.3901/jme.2018.08.026.

[13] X. D. Pan, X. H. Liu, and C. Li, "Research on NVH optimization of high-speed gear transmission for pure electric vehicles," *Journal of Chongqing University of Technology (Natural Science)*, vol. 31, no. 11, pp. 25–31, 2017.

[14] Y. Wang, L. Zhang, Y. Li, *et al.*, "Order spectrum analysis and ghost order identification of electric vehicle gear tooth waviness," *IEEE Access*, vol. 12, pp. 112345–112356, 2024.

[15] X. Chen, Y. Liu, and H. Wang, "Tooth surface waviness extraction and NVH correlation analysis based on iterative Fourier decomposition," *Mechanical Systems and Signal Processing*, vol. 189, Art. no. 110789, 2024.

[16] Y. Zhang, Y. J. Jiang, Y. Sun, *et al.*, "Gear tooth surface modification analysis by support vector machine regression," *Journal of Computational Methods in Sciences and Engineering*, vol. 23, no. 1, pp. 117–131, 2023. DOI: 10.3233/jcm-226521.