

## **ANALYSIS OF DEVIATION SHAPES ON NOISE-CAUSING GEARS**

**Hao Lyu, Zhaoyao Shi, Shitao Wang**

*Beijing Engineering Research Center of Precision Measurement Technology and Instruments,  
Beijing University of Technology, Beijing, China (✉ [shizhaoyao@bjut.edu.cn](mailto:shizhaoyao@bjut.edu.cn))*

### **Abstract**

In modern industrial applications, gears serve as pivotal transmission components, whose transmission performance is critical to operational stability of mechanical systems. For electric vehicles subject to stringent noise control specifications, the suppression and control of gear transmission noise carry heightened importance. To tackle gear noise at its root cause, this paper regards gear deviations as the primary excitation source of vibration and noise and systematically analyses six typical gear deviation shapes as well as the corresponding tooth-pair change-over characteristics in meshing. In addition, the mechanism of formation of the corner contact phenomenon and its influential effect on gear transmission errors are being investigated in depth. On this basis, in this paper a novel least-squares sine wave fitting method is proposed. The results demonstrate that the proposed method can effectively achieve the separation and quantitative characterisation of diverse gear deviations. Meanwhile, this paper conducts an in-depth analysis of transmission errors in noise-causing gears, verifying that eccentricity error, pitch deviation and tooth surface texture of gears are the key influencing factors dominating transmission errors and subsequent noise excitation. This research provides a refined analytical paradigm and reliable technical support for the precision quality evaluation and noise fault diagnosis of gears.

**Keywords:** cylindrical gear, metrology, gear deviation, transmission errors.

### **1. Introduction**

Gears are essential components for transmitting motion and power, and they play a critical role across a wide range of industrial applications as well as in daily life [1]. Their importance comes from their ability to achieve efficient and precise transmission, ensuring that complex machinery and equipment operate smoothly and reliably. The performance of gears directly influences not only the operational smoothness of the system, but also its long-term stability, service life, and energy efficiency [2]. In modern engineering applications, particularly where compactness and high efficiency are required, gears remain indispensable due to their high load-carrying capacity, reliability, and versatility.

In recent years, the rapid development of new energy vehicles has placed increasingly stringent requirements on the performance of transmission systems. In particular, the increasing demands in the field of new energy vehicles have led to stricter requirements for gear vibration and noise control [3, 4]. To address these challenges, gear topology modification has emerged as an effective and widely adopted solution. Topology modification refers to deliberate adjustment of gear tooth profiles that leads to optimisation of load distribution, minimising localised stress, and improving meshing behaviour. This technology not only improves the transmission performance of gears, but also significantly reduces vibration, impact, and dynamic transmission error during operation [5]. Consequently, gear topology modification has become a critical tool in modern gearbox design, particularly for applications requiring high precision and low noise.

Among the various challenges in gearbox engineering, gear noise is one of the issues of greatest concern. Excessive gear noise not only affects user comfort but can also serve as an indicator of underlying mechanical defects that can compromise system reliability. Gear noise originates primarily from impacts between the teeth of the driving and driven gears during meshing, as well as from resonance caused by periodic errors on the tooth flanks [6–8]. In essence, gear deviations – including profile errors, pitch deviations, lead deviations, and surface waviness – are the main causes of such noise. When gear deviations are not effectively controlled, they can lead to unpredictable dynamic behaviour, resulting in excessive vibration, unstable operation, and, in severe cases, premature system failure [9–11]. Consequently, the inspection and analysis of gear deviations are critical. Diagnostic results not only provide timely feedback to optimise the manufacturing process, but also enable accurate predictions of gear performance, ensuring the reliability and stability of the system [12].

Considerable research has been conducted worldwide on the effect of gear deviations on vibration and noise. For example, Gravel proposed a method for identifying noisy gears by focusing on ghost orders in the ripple signal [13]. This approach highlighted the connection between ripple patterns and gear noise characteristics, offering a pathway for diagnosing noise-related defects. Based on this, simulation-based ripple analysis has been developed to compare measured and calculated spectra, allowing the identification of excitations introduced during the machining process and pinpointing the underlying causes of noise problems [14]. Furthermore, an extended methodology allows for rapid calculation of vibration effects on the resulting gear surfaces, providing a valuable means to assess the influence of process variations in advance and optimise manufacturing strategies before mass production [15, 16]. These methods have been successfully implemented in industrial practice, such as within the Klingelnberg Gear Measuring Machine, which has become a benchmark tool for analysing deviations and their impact on noise.

Nevertheless, existing approaches still have limitations. The majority of these techniques are particularly well suited for crowned gears, which represent only a subset of practical gear applications. In real engineering scenarios, various shapes of gear deviations are encountered, including complex combinations of profile, pitch, and surface waviness errors, which may exhibit different mechanisms of noise excitation. A comprehensive understanding of these deviation shapes and their relationship with noise generation remains a pressing need. Therefore, this paper presents an in-depth analysis of a broader range of deviation patterns in gears causing noise. By systematically examining the spectral characteristics, transmission error contributions, and excitation mechanisms associated with different deviation shapes, the work aims to provide a more complete framework for diagnosing gear noise and guiding both manufacturing improvement and design optimisation.





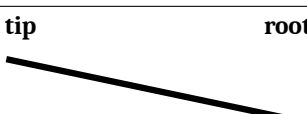

## 2. Gear deviation and tooth-pair change-over modes

Gear deviation refers to the deviation between the actual profile of a gear and its theoretically designed profile [17]. This deviation often arises from various factors during the gear manufacturing process, including machine tool inaccuracies, tool wear, fixture misalignment, thermal deformation, and even operator errors. This paper discusses gear profiles as examples, with similar analysis applied to the helix.

### 2.1. Gear deviation shapes

In actual transmission, the gear deviation shape can be divided into six types, as illustrated in Table 1, including ideal, sinusoidal, crowning, concave, negative pressure angle and positive pressure angle. The ideal profile maintains a perfect theoretical geometry for optimal meshing. Sinusoidal deviation creates a wavy pattern along the tooth flank, causing periodic transmission errors. The crowning features a convex profile across the width of the tooth to evenly distribute contact stress. The concave deviation forms a hollow curvature, leading to a stress concentration. The negative pressure angle deviation inclines the tooth tip outward, reducing the effective pressure angle. The positive deviation of the pressure angle slopes the tooth tip inward, increasing the pressure angle. These distinct deviation patterns significantly affect the transmission accuracy and noise characteristics.

Table 1. Results of numerical experiments for stationary and nonstationary filters.

Number	Deviation	Deviation chart
1	Ideal	
2	Sinusoidal	
3	Crowning	
4	Concave	
5	Negative Pressure angle	
6	Positive Pressure angle	

### 2.2. Modes of gear tooth-pair change-over

During gear transmission, when one pair of teeth change to follow another, a common meshing zone exists theoretically [18]. In this zone, the simultaneous meshing of the previous and next pairs of teeth allows for a smooth transfer of load from the previous pair to the next. When gears exhibit deviation, the smooth tooth-pair change-over between gear pairs is disturbed. Based on the six typical types of gear deviation shapes, gear tooth-pair change-over modes can be proposed, as shown in Table 2.

Table 2. Six typical types of gear tooth-pair change-over modes.

Number	Type	Gear Tooth Pair Change over Modes
1	Ideal	
2	Sinusoidal	
3	Crowning	
4	Concave	
5	Negative Pressure angle	
6	Positive Pressure angle	

### 3. Transmission error and gear deviation analysis

Transmission error refers to the difference between the actual position of the output and the ideal position that the output shaft of a drive would occupy if the drive were perfect [19–21]. Gear noise is not only influenced by the amplitude of transmission error but is also closely related to the tooth-pair change-over modes of the gear. According to the Integrated Gear Error Theory [22], the outer envelope curve of the gear tooth-pair change-over process represents transmission error. As shown in Table 2, the transmission errors in the case of multiple change-over, acceleration change-over, and deceleration change-over theoretically exhibit the “jump” phenomenon. In fact, due to the base pitch deviation, the gear undergoes a corner contact process instead of entering directly the involute meshing [23].

The transmission error during the acceleration change-over [24] is expressed as:

$$f(\varphi) = \begin{cases} (2Q\theta - u)\varphi - Q\varphi^2 & (0 \leq \varphi \leq \theta) \\ u(\gamma - \varphi) & (\theta < \varphi \leq \gamma) \end{cases}, \quad (1)$$

where:  $\theta$  – the contact angle of the corner,  $u$  – the constant value related to the gear parameters,  $Q$  – the constant value related to the gear parameters,  $\gamma$  – the standard pitch angle.

The transmission error during the deceleration change-over is expressed as:

$$\varphi = \begin{cases} u^*\varphi & (0 \leq \varphi \leq \lambda - \theta) \\ u^*\varphi - Q^*(\varphi - \gamma + \theta)^2 & (\lambda - \theta < \varphi \leq \gamma) \end{cases}, \quad (2)$$

where:  $u^*$  – the constant value related to the gear parameters,  $Q^*$  – the constant value related to the gear parameters.

The transmission errors during acceleration change-over and deceleration change-over are shown in Fig. 1.

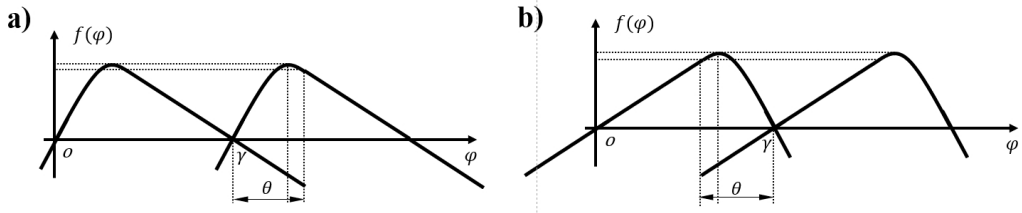


Fig. 1. Transmission errors with change-over: a) acceleration change-over, b) deceleration change-over.

During corner contact, the shape of the transmission error is a parabola instead of a “jump”. Based on the above analysis, the transmission errors for multiple change-over, acceleration change-over, and deceleration change-over should be modified, as illustrated in Table 3.

Table 3. Six typical types of gear tooth-pair change-over modes.

Number	Type	Transmission errors (red)
1	Ideal change-over	
2	Smooth change-over	
3	Change-over of the tooth flank	
4	Multiple change-over	
5	Acceleration change-over	
6	Deceleration change-over	

For separating gear deviations, this paper adopts a method based on least squares fitting of a sine wave function. By identifying the wavelength, amplitude, and phase of the sine function, the periodic components in the gear deviations are extracted.

The mathematical model for fitting is defined as follows:

$$\sum_{j=1}^N \left( y_j - A_k \cdot \sin \left( 2\pi \cdot \frac{x_j}{\lambda_k} + \varphi_k \right) \right)^2 \rightarrow \text{Min}_{A_k, \lambda_k, \varphi_k}, \quad (3)$$

where:  $\lambda_k$  – the wavelength,  $A_k$  – the amplitude corresponding to a wavelength of  $\lambda_k$ ,  $\varphi_k$  – the initial phase corresponding to a wavelength of  $\lambda_k$ ,  $x_j$  – the rotation angle,  $y_j$  – the transmission error value.

The results of the spectral analysis are shown in Fig 2, where the “meshing orders” are coloured blue, and the “ghost orders” are coloured red.

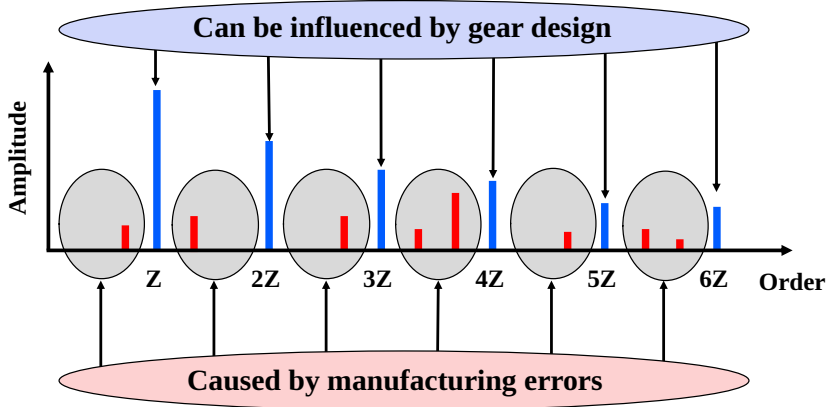


Fig. 2. Results of the spectral analysis.

#### 4. Analysis of gear transmission error

Transmission error is a key factor that affects gear noise and performance and is closely related to various forms of gear deviations. This section analyses the transmission error characteristics under different deviation conditions, including tooth-pair change-over, eccentricity, and pitch deviation, as well as irregular tooth surface texture.

##### 4.1. Analysis of typical gear transmission errors

The transmission errors shown in Fig. 3 are analysed. The gear parameters are teeth number 21, module 1.658 mm, and pressure angle  $20^\circ$ . The amplitude of the profile deviation for each gear is identical. For the ideal change-over, the transmission error contains no harmonic components, as shown in Fig. 3a. The smooth change-over exhibits only the component corresponding to the 1<sup>st</sup> meshing order, as shown in Fig. 3b.

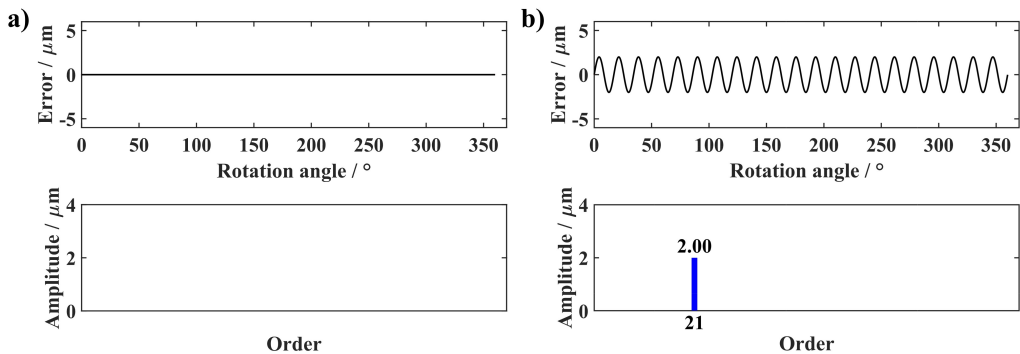


Fig. 3. Analysis of typical transmission errors: a) ideal change-over, b) smooth change-over.

The tooth flank change-over includes only the multiples of meshing orders, as shown in Fig. 4a. In the multiple change-over, its spectral analysis contains meshing orders with larger amplitudes, as shown in Fig. 4b.

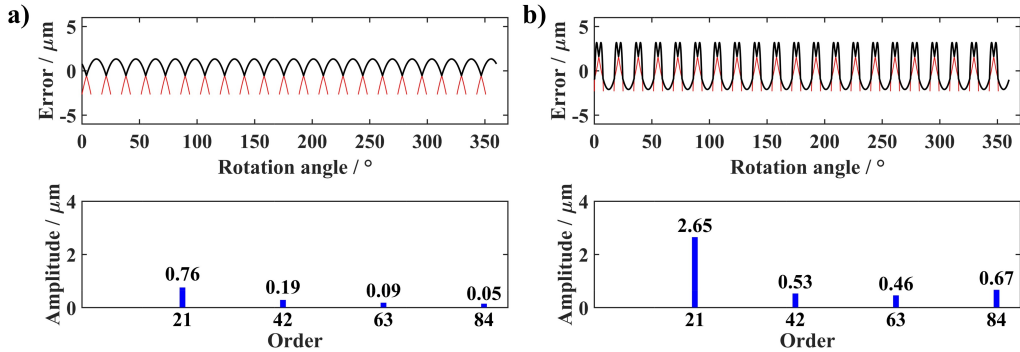


Fig. 4. Analysis of typical transmission errors: a) tooth flank change-over, b) multiple change-over.

For both acceleration change-over and deceleration change-over, the spectral components show identical orders and amplitudes, as shown in Figs. 5a and 5b, despite the different transmission errors.

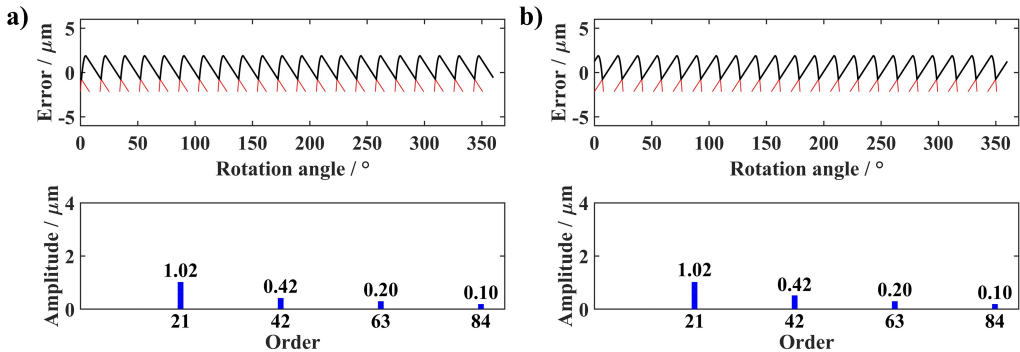


Fig. 5. Analysis of typical transmission errors with change-over: a) acceleration change-over, b) deceleration change-over.

#### 4.2. Analysis of typical gear transmission errors

Figure 6a presents the analysis results under an eccentricity-free condition, which yields a smooth transmission error curve with frequency content exclusively at the meshing order and its harmonics. Figure 6b shows a transmission error with eccentricity, where the component of the 1<sup>st</sup> order represents the radial runout caused by the eccentricity of the gear. If the radial runout contains multiple sine waveforms, it will extend along the tooth flank meshing order to both sides, forming sidebands at both ends of the meshing order, as shown in Fig. 6c. Figure 6d demonstrates the effect of pitch deviation, resulting from the wear of the grinding wheel, which leads to a gradual thickening of the gear profile. During grinding, the transition from the last tooth slot to the first introduces a significant pitch deviation, generating multiple harmonic components in the spectrum instead of traditional sidebands.

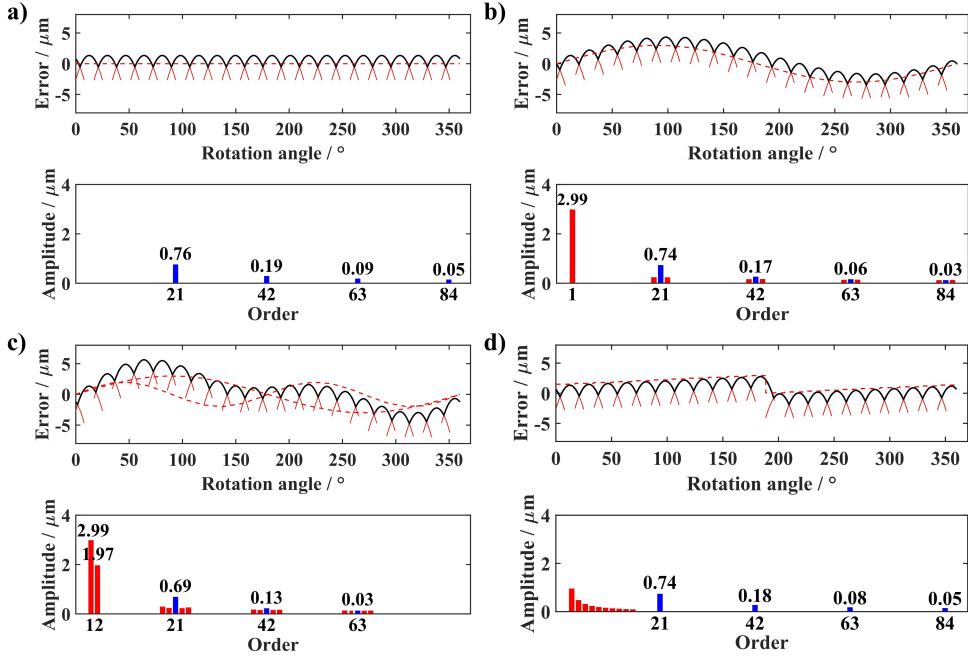


Fig. 6. Analysis of transmission error: a) eccentricity-free condition, b) eccentricity radial runout, c) radial runout and double strike, d) pitch deviation.

### 4.3. Analysis of transmission error with irregular tooth surface texture

The texture of the tooth surface is closely linked to noise behaviour. By improving irregular micro-geometries, such as surface waviness and roughness, significant reductions in noise and vibration at the contact tooth flanks can be achieved. Figure 7 shows the texture of the tooth surface with manufacturing errors, where a peak with an amplitude of  $0.30 \mu\text{m}$  appears at the 67<sup>th</sup> harmonic position, indicating the presence of an error component with a period of 67 in the transmission error. Analysis reveals that this component originates from the surface texture introduced during the processing of the tooth flanks. It is the irregularities in the tooth surface texture, resulting from the processing, that give rise to ghost orders in the spectrum. These ghost orders primarily contribute to the whine noise of the gear during meshing.

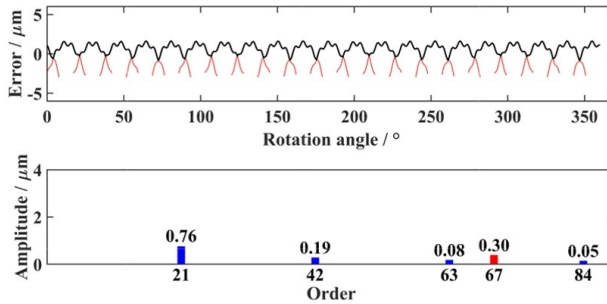


Fig. 7. Analysis of transmission errors that contain ghost orders.

## 5. Experimental analysis

Figure 8 shows the Klingelnberg P26 gear measuring centre that was used to measure the measured gear. The measurement items included key gear geometric accuracy parameters such as profile deviation, helix deviation, and cumulative pitch deviation, which were quantitatively evaluated according to the ISO 1328-1:2013 standards. The instrument's integrated multi-axis probing system and advanced evaluation software ensured traceable measurement uncertainty below 0.5  $\mu\text{m}$ . The gear measurement parameters are shown in Table 4 below.

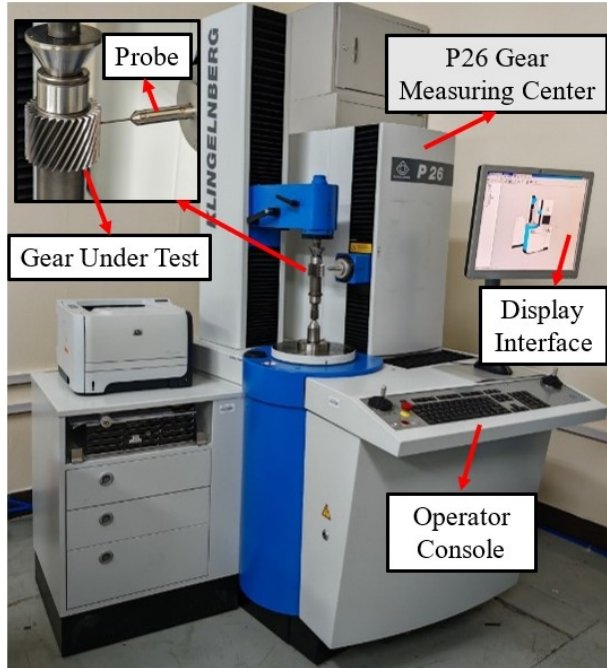


Fig. 8. Measurement on the gear measuring centre (Klingelnberg P26).

Table 4. Measured gear parameters.

Number of Teeth	Module/mm	Pressure angle/ $^{\circ}$	Helix angle/ $^{\circ}$	Face width/mm
21	1.658	20	23.2	32

### 5.1. Analysis of transmission error with irregular tooth surface texture

So far, the noise analysis of gear deviations has not considered the effect of corner contact on gear transmission error. Actually, the effect of corner contact on gear transmission error is apparent, taking a gear with negative pressure angle deviation as an example, as shown in Fig. 9. The comparison is shown in Fig. 10. When corner contact is considered, the amplitude of the first meshing order is large, but that of other meshing orders is smaller. Therefore, in the analysis of transmission errors, the corner contact should not be overlooked.

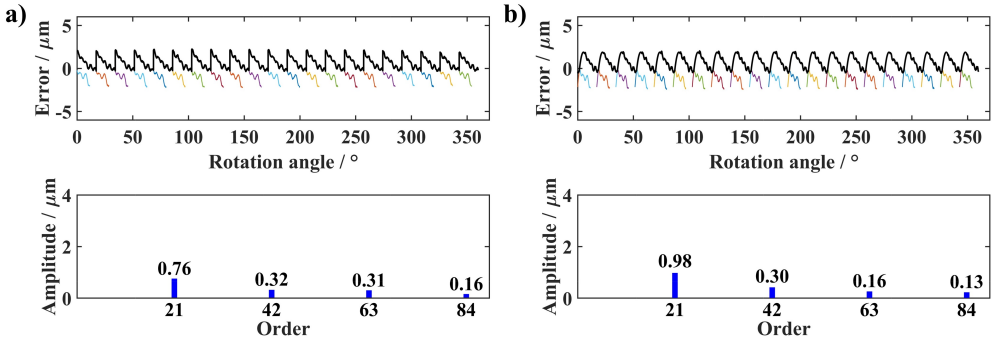


Fig. 9. Comparison analysis: a) not considering corner contact, b) considering corner contact.

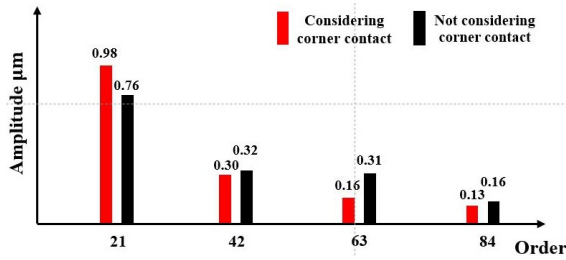


Fig. 10. Comparison analysis with and without considering corner contact.

## 5.2. Effect of pressure angle deviation on gear transmission error

Figure 11a shows the analysis results at a pressure angle of 20 degrees. From the analysis of Fig. 9b with negative pressure angle deviations and Fig. 11b with positive pressure angle deviations, it can be observed that the spectral results remain identical if the absolute values of the positive and negative pressure angle deviations are equal. Actually, impact of meshing-in occurs in gears with a negative pressure angle deviation, while the impact of meshing-out occurs in gears with a positive pressure angle deviation [25]. The noise of the former is much greater than that of the latter. Therefore, there is the possibility that inaccurate noise prediction occurs in spectral analysis based on gear deviation.

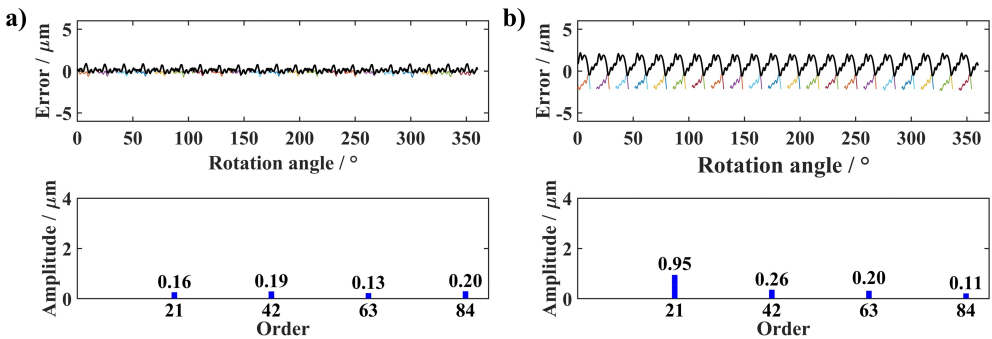


Fig. 11. Comparison results: a) standard gear, b) gear with positive pressure angle deviation.

### 5.3. Ghost orders in gear transmission analysis

In practical gear transmission systems, ghost orders refer to spurious frequency components that are not directly related to the gear meshing process. In the measurement results shown in Figure 12, ghost orders were identified at the 26<sup>th</sup> and 47<sup>th</sup> orders, each exhibiting an amplitude of approximately 0.05  $\mu\text{m}$ . Although their amplitudes are relatively small, these ghost orders can still have a significant impact on gear whine noise by introducing non-physical excitations into the system. Such spurious components can excite system resonances or interfere with the natural meshing harmonics, thereby amplifying tonal noise.

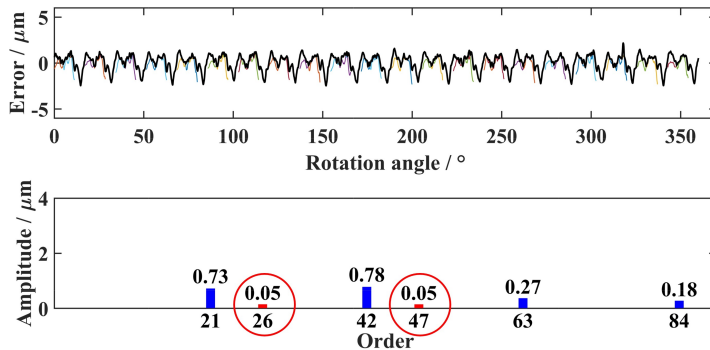


Fig. 12. Ghost order noise-causing gear whine noise.

### 5.4. Guidelines for industrial application

In industrial practice, the six typical gear deviation shapes and their corresponding tooth-pair change-over modes should be incorporated into routine inspection standards. Priority should be given to the measurement of corner contact-related parameters, and the proposed least-squares sine wave fitting method should be adopted to quantify the deviations of non-drum gears. For gear noise fault diagnosis, both time-domain and frequency-spectrum analyses should be combined. When ghost orders are detected, the machining quality of the tooth surface should be improved. During the manufacturing process, targeted control should be implemented on key gear deviation sources – for example, eccentricity error can be reduced through fixture calibration, and pitch deviation can be alleviated by dressing grinding wheels. Priority should be given to the correction of negative pressure angle deviations. The corner contact effect should be integrated into gear design and a parabolic transmission error model should be employed to optimise the tooth profile, so as to reduce vibration and noise in high-precision applications such as transmissions for new energy vehicles.

## 6. Conclusions

As pivotal transmission components, the gears directly determine the operational stability of mechanical systems. In the field of electric vehicles subject to stringent noise control specifications, the control of gear transmission noise is particularly critical. To tackle the problem of gear noise at its root cause, this study analyses gear deviations, corner contact meshing, and transmission errors of gear pairs, and the main conclusions are drawn as follows.

- 1) A novel least-squares sine wave fitting method is proposed to separate gear deviations. It is found that the parabolic surrogate model of corner contact increases the amplitude of the first-order meshing frequency spectrum while reducing the amplitudes of other order components, revealing that the effect of corner contact cannot be neglected in transmission error analysis.
- 2) Six typical gear deviation shapes and six gear pair tooth-pair change-over modes are identified, and the gear transmission errors under different modes are analysed, with special attention paid to the key influencing factor, i.e. corner contact.
- 3) For gears with significantly distinct noise characteristics caused by positive and negative pressure angle deviations, the results of spectral analysis exhibit similarity, indicating that relying solely on spectrum analysis for noise-causing gear fault diagnosis has inherent limitations.

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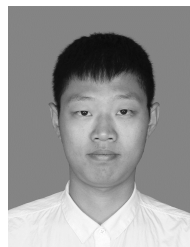
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**Zhaoyao Shi** received his B.Sc. degree from the Hefei University of Technology in 1984, his M.Sc. degree from the Shanxi Institute of Mechanical Engineering in 1988, and his Ph.D. degree from the Hefei University of Technology in 2001. Currently, he is a professor and Ph.D. supervisor at the Beijing University of Technology and a holder of the Yangtze River Scholar title, which is a special professor award by the Ministry of Education. His main research interests are precision measurement

technology and instruments.



**Hao Lyu** received his B.Sc. degree in measurement and control technology and instrumentation from Tangshan University in 2018. He is currently a postgraduate student at the Beijing University of Technology. His main research interests are precision measurement technology and instruments.



**Shitao Wang** obtained his M.Sc. degree in mechanical engineering from Shijiazhuang Tiedao University, China, in 2020, and is currently pursuing a Ph.D. degree in mechanical engineering at the Beijing University of Technology, China. He is currently a lecturer with North China University of Science and Technology, China. His research activity focuses on NVH measurement of electric vehicle gears, as well as analysis and traceability of gear manufacturing errors.