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Parametric influence of gear surface and geometric features on dynamic performance

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Abstract

Gears are the heart of mechanical powertrain systems used in diverse power transmission applications. Traditionally, gear design and validation have focused on static geometric measurements. However, a gear's dynamic performance is significantly impacted by its surface integrity and micro-geometric features introduced during manufacturing. These parameters, including surface roughness, waviness, profile deviations, and tolerances, influence transmission error, vibration noise, and load distribution, ultimately affecting the gear's fatigue life. This study presents a focused and concise overview, linking gear geometric parameters to dynamic performance. This shift aims to advance gear design beyond traditional static evaluation towards performance-driven strategies. This concise review synthesises findings from experimental studies, analytical models, and industrial practices to assess dynamic behaviour like noise, vibration, and harshness monitoring (NVH), as well as dynamic load-dependent testing. It also outlines future directions, including data-driven predictive models, real-time condition monitoring, and smart gear system integration.

Keywords: Gear; Surface integrity; Dynamic performance, Industrial applications.

1. Introduction

The gear systems operate under complex dynamic conditions such as variable loads, fluctuating speeds, and transient operating states. Their functional performance is not only governed by macro-geometry but also by the condition and quality of the tooth surface, where power transfer physically occurs. Vibration and noise measurement are known to contain valuable information about gear behaviour, allowing engineers to detect gross defects, misalignment, and certain irregularities [1,2]. Most research and industrial practices focus on defect detection rather than systematically linking specific gear parameters such as profile, lead, pitch, micro-geometry, surface roughness, and waviness to quantitative functional performance outcomes like vibration noise and load distribution [1,3].

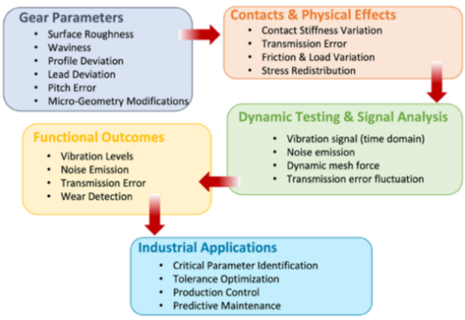

Figure 1. Integrated Framework Linking Gear Surface and Geometric Parameters to Dynamic Functional Performance and Industrial Decision-Making (own study).

However, there is still limited understanding of which parameters are more critical to dynamic behaviour, and the industry lacks a standardized method to use dynamic test data for design optimisation, production control, and tolerances refinement beyond simple pass/fail inspection. Addressing these gaps, this concise review aims to synthesise current knowledge on how surface and geometric features influence dynamic performance, highlight functional validation methods including Fast Fourier Transform (FFT)-based signal analysis, and provide insight to identify critical parameters, improve vibration and noise characteristics, optimise load distribution, and enable performance-driven design and production strategies. Fig. 1 presents an integrated framework that maps gear surface and geometric parameters to dynamic performance indicators, highlighting its potential to support performance-driven industrial design, tolerance optimization, and production control.

2. Surface and geometric features

Surface characteristics of a gear, such as roughness, waviness, and micro topography, play a significant role in the dynamic response of gear systems. Surface roughness contributes to local frictional excitation during tooth engagement, while waviness can induce local stiffness variations that can amplify vibration at specific frequencies [4]. Cheng et al. investigated the intimate connection between the contact surface properties and gear performance, demonstrating that both contact stiffness and damping decrease as surface roughness increases [5]. Gear NVH is highly sensitive to surface waviness, where even extremely small periodic deviations (0.1-1 µm) on the flanks can produce ghost frequencies [6]. Micro geometry modifications, including profile relief, lead crowing, and pitch adjustment, may control load distribution and minimise peak contact stresses. Variations in these parameters can directly influence the transmission error, modulate dynamic mesh stiffness, and excite vibration modes, which in turn affect noise generation and operational efficiency [4]. A conceptual mapping of gear surface and geometric parameters to functional outcomes reveals clear relationships between specific features and dynamic behaviour. Understanding these relationships allows engineers to prioritize design and manufacturing efforts on the most influential parameters, implement targeted quality control, and optimise operational performance. This functional perspective provides a framework for production-driven decisions, ensuring that industrial gear systems meet performance criteria effectively and reliably.

3. Functional performance and dynamic response

Functional performance metrics, including vibrations, noise, and load distribution, provide critical insights into gear behaviour under operational conditions [2]. Condition monitoring of gear, specifically through vibration signal analysis, has emerged as an effective strategy for early fault detection and for reducing unexpected downtime. Transmission error represents the instantaneous deviation between the theoretical and actual angular displacement, a key indicator linking geometry and surface characteristics to dynamic response [6]. FFT-based signal analysis is widely used to identify dominant excitation frequencies and sidebands generated by deviations in microgeometry and surface quality. Functional validation may enable identification of which parameters influence the dynamic performances, and each tolerance may be relaxed without compromising NVH.

By prioritising functional performance over purely geometric compliance, industries can transition towards performance-driven design and production strategies. Furthermore, data-driven approaches such as machine learning models have demonstrated potential in predicting noise test outcomes based on measured manufacturing data. These models facilitate proactive management of gear NVH through predictive quality control [6].

4. Dynamic testing

Dynamic testing has proven to be a powerful approach for evaluating gear dynamic response beyond traditional static geometric measurements. Dynamic testing methods include accelerometers for high-speed vibration measurement, torque transducers, and strain gauges combined with FFT-based spectral analysis to quantify transmission error, vibration amplitude, and noise levels [7]. Furthermore, dynamic testing is commonly employed to detect gear wear as progressive surface degradation alters contact conditions and modulated mesh stiffness.

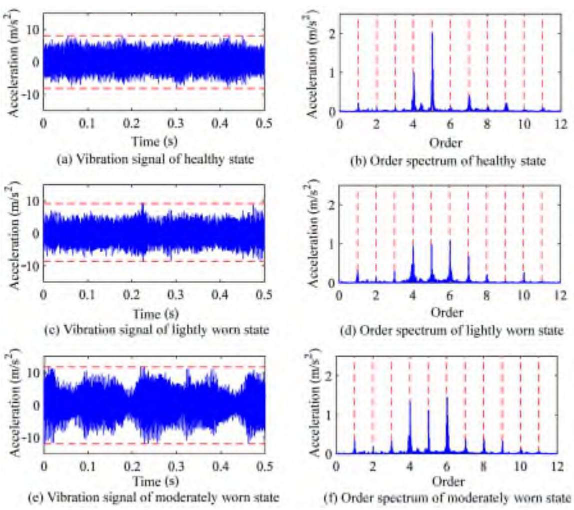

Figure 2. Gear vibration signals and corresponding order spectra at an operating condition for healthy, lightly worn, and moderately worn gear conditions [7].

This enables the identification of early wear patterns, the prediction of maintenance requirements, and the validation of design and micro-geometry modifications (Figure 2). Despite these benefits, such functional testing approaches remain primarily research-focused and are not yet standardized in industrial production, representing a significant opportunity for integrating performance-driven evaluation into manufacturing workflow.

5. Industrial implications and production control

Mapping surface and geometric parameters to functional performance has direct industrial relevance. Identifying parameters that most significantly affect vibration, and noise may enable targeted improvements in micro-geometry, surface finishing, and manufacturing processes, optimising production efficiency while minimising cost. Functional validation will allow selective relaxation of certain geometric tolerances without compromising operational performance, provide greater design freedom, and reduce the need for over-precision. Integration of dynamic test data into production and quality control protocols supports predictive maintenance, enhances consistency of gear behaviour, and reduces unplanned downtime. By linking parametric knowledge to functional outcomes, industries can achieve better gear dynamic performance and, overall, more reliable and efficient gear systems. Mitigating gear NVH demands excellence in both design and manufacturing, as literature consistently shows that achieving optimal performance requires the integration of both rather than relying on them in isolation.

6. Conclusion

Surface and geometric features, including roughness, waviness, and microgeometry, significantly affect gear dynamic performance, influencing vibration, noise, and load distribution. Function performance evaluation through dynamic testing and FFT-based analysis enables systematic identification of critical parameters, offering opportunities for tolerance optimisation, wear monitoring, and design improvement. Incorporating functional validation into industrial practice supports performance-driven design, production control, predictive maintenance, and enhanced quality assurance. By moving beyond traditional static measurements, engineers and researchers can develop the most robust, efficient, and sustainable gear systems, ensuring operational reliability and optimising manufacturing efficiency.

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