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Dynamic Analysis Of Spur Gears With Crack Propagation: Influence Of Contact Location And Load Direction On Pinion Rotation Behavior

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Abstract
This research examines the impact of different contact locations (CL) and load orientations on the dynamic behavior of cracked spur gears. The pinion rotation angle was examined using vibration analysis methodologies for three clearance levels (1.5 mm, 2.5 mm, and 3 mm) at various load angles (15°, 30°, and 45°) directed towards the rim and the tooth. Results demonstrate that with reduced CLs, significant fluctuations in pinion rotation angle occur, exhibiting increased sensitivity to load directions. As the CL grows, these fluctuations decrease, resulting in more stable behavior. The results provide understanding of fracture propagation behavior, allowing superior gear condition monitoring and fault diagnosis for increased durability and performance.

Keywords: *Spur gear, Crack, Pinion, Gear mesh stiffness*

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I. Introduction

Gears are often used for mechanical power transmission in commercial, automotive, and daily life applications. Gears has an advantage in modifying the direction of rotation, efficiently transmitting substantial loads and establishing a high-speed ratio, contingent upon the arrangement of the gearing system. Excessive load application, manufacture faults, installation difficulties, or insufficient lubrication may result in gear failure. Gear loss is an undesirable occurrence, since it necessitates the interruption of the gear's operational capacity, potentially resulting in significant and costly repercussions. Implementing an effective maintenance program may reduce mistakes and unanticipated interruptions by facilitating the early detection of gear malfunctions. System Status Control ensures optimal performance and cost-effective service. Condition Tracking may provide early warnings of system failures, enabling remedial actions to be implemented prior to the fault causing malfunctions and possibly catastrophic losses. Investigating gear deterioration via vibration signals is of special importance. Vibrational impulses from gears are complex and difficult to comprehend. Vibration analysis techniques may be categorized into time domain and frequency domain methods for condition monitoring. To monitor parametric or pattern changes when transmission components degrade, temporal analysis methods using predictive analytics on filtered or direct time signals are used. To evaluate overall wear from tooth-specific injuries, statistical analyses including standard deviation and kurtosis are used.

Frequency analysis, or spectrum analysis, of vibration signals is an additional method for analyzing the information included within the signal. The failure diagnosis of two gearboxes, based on frequency analysis of the vibrations generated by speed reducers, has shown limitations in spectral resolution. Various adaptations of spectrum analysis and time-frequency analysis, including cepstrum analysis, wavelet analysis, and spectral kurtosis, have been used for gear defect diagnostics. A substantial body of study has been conducted on the singular fracture in a gear using various condition monitoring and signal processing methodologies. Nevertheless, comprehensive investigations on the evolution of faults and the impact of numerous fractures on gears under varying operating situations have not been conducted in detail. The majority of studies have examined fault diagnostics for individual cracks. The examination of a single fracture has separately evaluated crack propagation to the root and crack propagation to the rim.

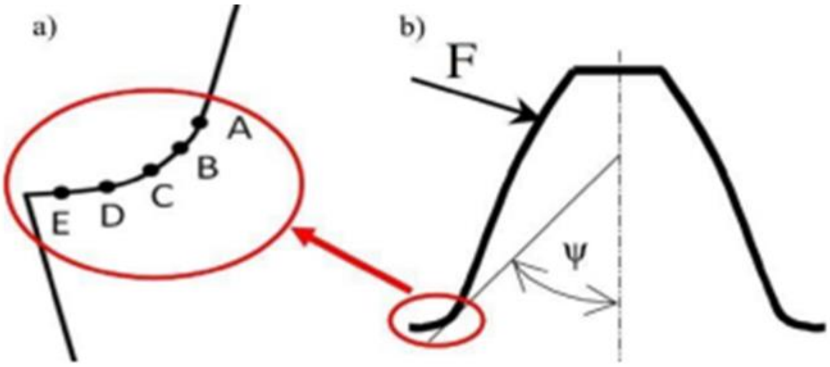

Fig. 1 (a) Initial position of propagation of crack (b) Tangential view

Scenarios of Crack Propagation

Numerous scholars have proposed distinct scenarios of fracture propagation that may be used to simulate this phenomenon; the most notable include: The fracture extends uniformly throughout the whole width of the tooth.

- This scenario is modified when a uniformly distributed load is assumed. In this instance of crack propagation, the stiffness of a fractured tooth is inferior than that of the subsequent two occurrences.
- In a parabolic fracture length distribution, the crack extends throughout the whole width of the tooth. This scenario is adjusted when a non-uniformly distributed load is assumed. In this propagation scenario, the stiffness of the shattered tooth is essential because to its little mobility.
- Simultaneously, the fracture advances in both the longitudinal and lateral directions, making it more applicable than the prior model for scenarios with non-uniform load distribution.

II. Literature Review

Ma and Zeng (2015) noted that after establishing the propagation route, the associated time-varying mesh stiffness may be computed by theoretical or experimental approaches. The altered time-dependent mesh stiffness may lead to variable dynamic responses. The study found that, in addition to time-varying mesh stiffness, geometric transmission error and bearing stiffness significantly impacted the dynamic responses of a fractured gear rotor system. To comprehend the synergistic effects of tooth cracking and plastic inclination, a model for plastic inclination must be established for a spur gear pair, using the fractured tooth as a variable cross-section cantilever beam. Meagher and Wu (2010) noted that monitoring techniques like mounted accelerometers often face challenges in data interpretation due to the multitude of gear mesh frequencies and the considerable noise present. The lumped parameter approach was determined to compute the stiffness of involute gears using just two parameters, resulting in a more rapid calculation compared to other methods. This strategy also delineated the relative contributions of various components of compliance. It was determined that multi-body kinematic methods are adaptable however need significant user time to create a model for each distinct combination of gears. Mohammed (2013) used dynamic lumped parameter modeling to extract the dynamic response of a gear system, examining the impact of tooth fracture propagation on the vibration response from a fault detection perspective. A dynamic simulation was conducted on a 6 DOF model using a time-varying mesh stiffness model. The significant parameter added herein was the frictional force resulting from the sliding interaction between the engaged teeth. The model presumes a linear decrease in effective tooth thickness, which is suitable for small fracture sizes that provide an approximate match; however, for bigger cracks, the linear approach begins to eliminate an effective area that should be considered in stiffness assessment. The straight line does not accurately delineate the presumed exclusion zone. Parey and Sharma (2015) conducted a literature study on condition indicators for fault diagnosis in fixed-axis gearboxes, focusing on their characteristic frequency and statistical metrics for fault identification. It was discovered that vibration signals are inherently complicated, and gearboxes with several meshing pairs complicate fault identification. They determined that the input frequency of the whole gear transmission will match the rotational frequency of the gear, and the selection of the damage indication is not directly connected to sensitivity. They have shown several status indicators derived from defect detection approaches, considering the impact of variable load and oscillating speed. Parey and Tandon (2003) investigated the impact of vibrations on gears and the numerous flaws in gears that induce vibrations. They have elucidated many concepts used in Gear Dynamic Modeling, including flank deviation, dynamic factor, transmission error, backlash, and external excitation. They presented many instances of impact concerning the influence of mesh stiffness on the tooth surface, using a graph that illustrates gearing stiffness as a function of time for a single period. Various mathematical models, along with their shortcomings, have been developed to include the effects of friction in relation to the equations of motion. Friction enhances the degree of freedom in any dynamic model perpendicular to the contact line of the meshing teeth. Sliding wear on the gear flank reduces the dynamic contact load. Yu (2015) discovered that in ideal gear pairs devoid of design and manufacturing imperfections, such as tooth profile and tooth pitch faults or 14 modifications, the load fractions of the interlocking tooth pairs must provide equivalent mesh deflections inside the double contact zone. The presence of a fracture will result in less gear mesh stiffness and a decrease in the load borne by the cracked tooth pair, particularly during first engagement of the cracked tooth pair. If a fracture propagates away from the tooth root along the tooth profile, it often results in a lesser drop in gear mesh stiffness and load sharing ratio compared to normal conditions.

III. Methodology For Crack Propagation And Gear Mesh Stiffness

Techniques

The precise crack propagation route is crucial for appropriately assessing the dynamic properties of damaged gear systems. A significant portion of material detaching from a component is termed a fracture. It is produced by the formation of a fracture or by the amalgamation of many cracks. The two primary types of gear tooth fracture are flank fracture in the center and bending fatigue at the gear root. fracture formation is triggered by overload, fatigue, and chemical corrosion, and typically advances until the fracture intersects a free surface and merges with adjacent cracks. The characteristics of crack appearance and fractures vary based on the fracture process, material type, and stress circumstances. Propagation routes are clean, continuous, and linear, exhibiting relatively little curvature, whereas tooth cracks mostly originate in the crucial region of the gear tooth root, where highest principal stress occurs. Efforts have been made to establish monitoring methods for problems in mechanical transmission systems. A significant fracture is seen in the spur gear under cyclic loading conditions. The factors influencing the fracture propagation route include the beginning crack angle, initial crack length, and initial crack propagation angle. The fracture propagation angle is determined by calculating the mode I and mode II stress intensity components. In hub rings of fractured gears, the degrees of freedom of the nodes are restricted. A solitary element is created at the fracture tip to determine the first crack parameters. The finite element model is used to compute the stress intensity components that include the singular element. In light of the crack propagation trajectories, the flexible body models of the driven and driving gears are created in ANSYS software. fracture propagation routes are derived based on the specific model section corresponding to various fracture phases. The gear tooth is modeled as a non-uniform cantilever beam on the base circle. The influence of rim and web thickness, beginning crack positions, and gear tooth geometry—including diametric pitch, tooth count, pitch radius, and pressure angle—was evaluated. FRANC 3D is used for analyzing gear fracture propagation towards the tooth and rim, as well as for many other circumstances. The program utilizes the principles of linear elastic fracture mechanics to analyze plane strain, plane stress, and axisymmetric situations. A distinctive characteristic of FRANC 3D is its capability to represent a fracture inside a structure. The application uses the "delete and fill" approach to achieve the functionality. The crack tip is positioned at a specified angle and at a user-defined incremental length. The model is then re-meshed using the delete function. This method is repeated a certain number of times as determined by the user. The advantage of using FRANC software lies in its automated crack propagation functionality. Upon the introduction of an initial fracture in the mesh, the software simulates crack propagation as a series of linear segments. The mathematical models created for crack-induced excitation and the state-space multi-degree-of-freedom model of the spur gear dynamic system in Chapter 3 have been used for analyzing crack propagation towards the tooth and towards the rim. The load analyzed in this study is supposed to consist of a static component of 200 N, accompanied by a variable component that is either harmonic or random in nature. The response spectra have been derived by the signal processing methodology. The lengths of the cracks have been altered to examine the impact of changes in crack propagation angle on the resulting spectra, and the results are elaborated upon in the subsequent subsections.

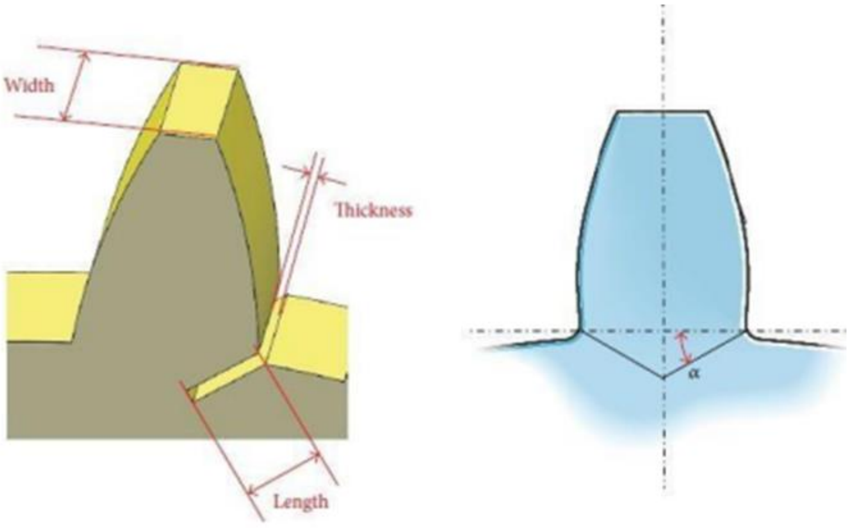

Fig. 2 Schematic view of crack

Table 1. Gear and pinion specifications

Parameter	**Gear/Pinion**
Tooth profile	Involute
Material used	Mild steel
Number of teeth	40/80
Modulus of elasticity	220
Poisson's ratio	0.33
Module	2.5
Pressure angle	20
Coefficient of tip clearance	0.25
Coefficient of addendum	1.5
Face width	12
Contact ratio	Greater than 2

This research examines single, double, and triple tooth contact pairings inside a gear system, using the criteria outlined in Table1. In a single pair, two gears interlock and exert equal force. In the event of a double pair, two pairs distribute the overall force, resulting in four teeth engaging simultaneously. In a triple pair configuration, three pairs distribute the overall force, with six teeth engaged concurrently. The overall effective mesh stiffness for a single tooth contact pair comprises the tooth mesh stiffness of gear 1 and gear 2. Similarly, for double and triple tooth contact pairs, the total mesh stiffness is determined by the direct summation of the individual tooth gear mesh stiffness, since the tooth pairs are regarded as operating in parallel. However, for an individual tooth pair, the gear and pinion teeth are regarded as a series combination. The mathematical equations are modeled in MATLAB, and the single pair tooth mesh stiffness of the pinion and gear is computed along the pinion roll angle.

IV. Results And Discussion

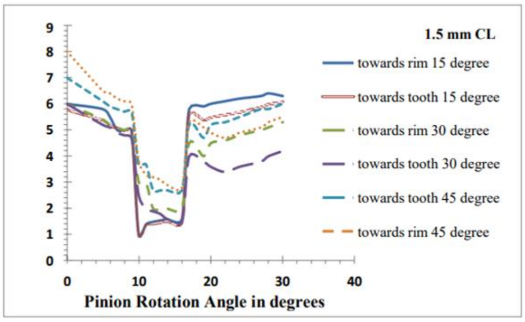

Fig. 3 Linear Crack Mesh Stiffness of 1.5 mm Crack length

The three graphs as shown in fig. 3, 4 and 5 depict the variation in pinion rotation angle (in degrees) for different load conditions at varying contact locations (1.5 mm, 2.5 mm, and 3 mm CL) and angles (15°, 30°, and 45°). Each graph highlights the influence of the loading direction, specifically towards the rim and tooth at respective angles. The graph (fig. 3) shows significant variation in the pinion rotation angle across all configurations, with the loading towards the rim at 15° exhibiting the highest values. A pronounced dip is observed around the 10-15° region, followed by a recovery. The graph (fig. 4) indicates a more consistent trend with slightly lower peak values compared to 1.5 mm CL. The curve for loading towards the rim at 15° still dominates, while other curves closely follow, indicating reduced influence of load variation. The variations become less pronounced ((see fig. 5), with all curves converging into a relatively uniform trend. The dips and recoveries are smoother, suggesting more stable behavior at this contact location. These observations indicate that as the contact location (CL) increases, the impact of load direction and angle diminishes, leading to more stable and consistent pinion rotation behavior.

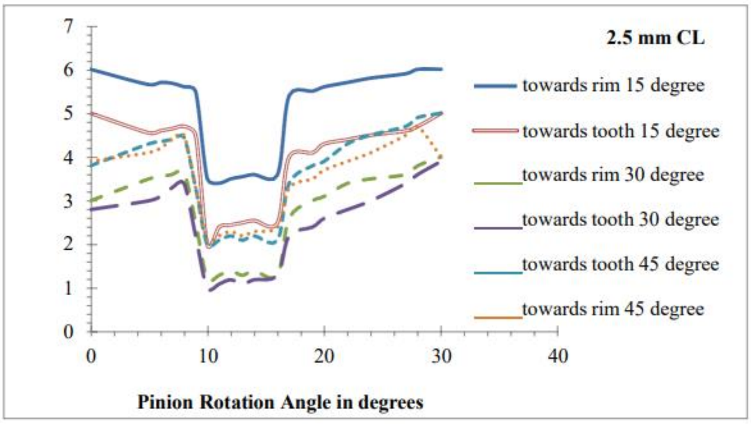

Fig. 4 Linear Crack Mesh Stiffness of 2.5 mm Crack length

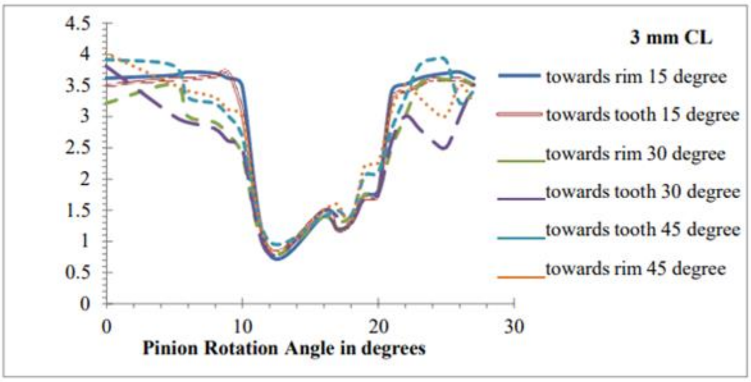

Fig. 5 Linear Crack Mesh Stiffness of 3 mm Crack length

V. Conclusion

The research emphasizes the considerable impact of crack propagation and load orientations on the dynamic behavior of spur gears. At smaller contact locations (CLs), the pinion rotation angle shows significant fluctuations, particularly under stresses applied towards the rim at 15°. As the CL grows, these deviations decrease, leading to more uniform behavior across load angles and orientations. This study underscores the need for accurate condition monitoring methods to identify flaws promptly and reduce the risks of gear failure. The results boost comprehension of gear dynamics, providing critical insights for the design of resilient gear systems with improved operating dependability.

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