Fractal Wear Behaviour of Gear Tooth: A Review

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Abstract Fractal wear behaviour of gears refers to failure mode of gears as a result of contact mechanics, which occurs while in application. Tooth-to-tooth surface damage usually ensues as a result of variation in excitation energy of the gear. This study therefore investigated the nature of fractal wear encountered by gear tooth with a focus on general fatigue wear, temperature-induced wear and different models for wear predictions. The result of the study showed that tooth surface damage such as fatigue, pitting corrosion and scuffing causes gear failure. Failure due to bending fatigue was observed to contribute to the maximum deflection of the gear tooth during rotation, thus resulting in excessive noise and vibration. Further to this, it was possible to predict the material removal rate of a failed gear using some of the highlighted empirical methods in the study. Based on these models, it will be possible to predict the nature of wear on gear tooth surface and use it during gear design.

Keywords Fractal wear · Gear tooth · Fatigue failure · Vibration

1 Introduction

The wear of gear tooth is regarded as a major factor to overall component failure and improvement in the mechanical properties of gear tooth to mitigate or reduce wear, which is important for reliability and availability of machines. Thus, it is necessary to assess the nature of gear failures in order to improve the design. Tooth wear in gears has been associated with misalignment at the tooth profile causing

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excessive noise and vibration resulting in eventual failure [1]. Miler et al. [2] noted that one major cause of the gear tooth misalignment is the variation in the profile shift, which introduces a stress factor that affects the optimal efficiency of the gear component. Although the profiles are usually specified and designed into the product during manufacturing, they pose a significant wear behaviour due to the alterations during manufacturing in order to meet the satisfaction of the customers [3]. This will cause radial and hoop stress along the tooth leading to crack initiation on the gear surface asperities and the tooth roots of the gear [4–6]. Despite numerous efforts by gear designers to predict wear behaviour of the gears using various tribo-dynamic models, the variation in speed of gears has remained a major factor to gear designers [7, 8]. More so, accuracy in wear detection and diagnostic approach has become a major problem at the initial stage of gear failure, thereby mitigating the use of numerical and experimental investigations of the increased tooth wear and acoustic emission monitoring devices [9–11]. Further to this, it was reported by Kumar et al. [12] that pitting occurred in gears as a result of increased rolling with sliding motion. The variation in load sharing contributed to gear deflections, which lead to increase in frictional loss along the gear tooth tip [13, 14]. In turn, the loss in frictional power can be increased by the surface roughness along the gear surface in mesh, thus making the oil film less effective in reducing wear [15]. However, there is an extent to which smooth gear surface is affected by surface roughness and once the grinding surface roughness is not well guided during production, it affects the profile of the involute [16, 17]. Based on this statement, it is worthy of noting that most gear failures are associated with error during the manufacturing process. For instance, gear shapers pose geometric and kinematic errors during gear shaping process, which affect the accuracy when compared to standards and cause excessive mesh stiffness that can affect the dynamic action of the gear system [18–20]. The variation in the mesh stiffness increases the transmission error between a pair of gear in mesh, thus increasing the torsional effects at the surface of the gears and leading to low performance during operation [21–25]. According to Jolivet et al. [26], the geometry of a finished gear tooth has an effect on the acoustic emission during operation. This will enable a gear specialist to measure the wear behaviour of the gear both in lubrication condition and in dry working condition in order to determine its optimal performance. Inaccurate finishing in tooth geometry causes excessive noise, vibration and eventual micropits on the surface asperities resulting in tooth deformation [27–30]. In an attempt to reduce wear and improve on gear performance, as well as durability, empirical models have been developed to study the dynamic characteristics of gears in mesh. For instance, Ni et al. [31] employed a numerical approach to improve the mesh behaviour of a bevel gear. However, the high-speed motion in bevel gear transmission was not considered and this can result in reduced bearing capacity of gear tooth surface, but studies have shown that gears of this type will not function well in some applications, which require high pressure due to increased frictional loss and scuffing failure [32–34]. In radial loads, lubricant temperature played a major role in the wear behaviour of the gear system [35]. Many experimental attempts have been employed in the treatment of gears in order to reduce wear but still left with great shortcomings. In the light of this, shot peening was adopted to improve the fatigue life of steel gears by Lv et al. [36]. However, the variation in speed and load still remains a major problem during fault detection [37, 38]. Although it was possible to detect faults through the interpretation of the data obtained from the dynamic signals, validation of the detected faults still remains a great challenge [39, 40].

2 Critical Problems Associated with Gear Wear Prediction Models

The frequent transmission error occurring during gear meshing has necessitated the application of several engineering models to predict the gear performance and the wear behaviour. Basically, the variation in impact load between meshing tooth can result in bending fatigue and pitting on the working surface. Although it was possible to predict the surfaces or teeth that are missing during operation using some simple empirical models, however, the failed gear tooth will show some evidence of material removal causing distortions on the involute profile. Models to predict this material removal rate are quite not easy to develop [41]. To this end, model development will need critical analysis of the thermal stress on the contact surface by considering the various points of acoustic emissions causing pitting at the tooth surfaces, which make the material susceptible to eventual deformation before adequate prediction of material removal rate can be ascertained [42–46]. Morales-Espejel and Gabelli [47] proposed a model for analysing the fatigue life of gears based on the load-carrying capacity of the machine. The model adopted a Weibull method to analyse the strength of the material and the Lundberg–Palmgren principle to investigate the load-bearing capacities. However, transmission error reduction requires a good surface finish and accurate microgeometry during gear manufacturing. The pressure distribution during contact is also a factor to surface fatigue prediction, which becomes a major challenge, especially in production of gears that have non-circular shape [48–52]. Technically, the developed model was possible for backlash reduction, especially on worm wheel gears, but to what extent would this improve the optimal working efficiency of the gear remains a major problem, unless the complex nature of the gear tooth kinematic geometry is well understood, which is a function of the nonlinear and acoustic behaviours of the gear system [53–57]. Based on this, Dhamande and Chaudhari [58] developed a statistical model for diagnosing the vibration of gears on the basis of speed and load condition in order to predict fatigue on the surfaces of the gear tooth. This is limited by the type of contact stress causing fatigue failure due to the fact that it is impossible to identify the stress in real-life situation [59]. More so, studies have revealed that simulations or experiments would give a better result because the parameters for vibration monitoring can be controlled overtime; however, in real-life applications, operation conditions are prone to these errors, thus making it impossible to get the exact point of stress causing incessant fatigue failure. In addition, complex mechanism of operation of the gear component limits the chances of fundamental fatigue, which causes the fracture of the tooth surfaces [60–63]. A number of researches have been carried out on the way to predict failures in gears by synchronizing the gear components with gear monitoring devices. For instance, Palermo et al. [64] suggested that a digital encoder can be integrated into the system to measure the transmission error during vibration. Besides, Li et al. and Ren et al. [65, 66] reported that angular displacement of gears during operation causes gear deflection along the path of travel and this will result in variation in the meshing mechanism of the gear. The studies further proposed that this problem can be monitored using angular displacement sensor to detect faults. Obviously, data obtained from angular signals are limited by variation in the speed of the machine and dynamic responses of the rotary component [67]. Reduction in degree of freedom and accurate gear mesh simulation might be of interest in reducing the surface fatigue [68].

3 Temperature-Induced Gear Wear

Heat generation exists at the interface of meshing teeth due to increased torque transmission, which constitutes a temperature zone, which can be referred to as bulk and flash temperature point on the gear tooth [69]. It was possible to say that the heat flux distribution along the path of contact induces thermal stress on the material resulting in thermal failure of the gear tooth [70]. The unsteady state temperature distribution can result in frictional heat generation and increased temperature rise on the gear tooth surface, which eventually reduces the transmission efficiency [71]. According to Castro and Seabra [72], the viscosity of the oil is a function of temperature and a coefficient of friction between a pair of gears in mesh. This, however, affects the scuffing load capacity of the gears. Bulk flash temperature variation is usually directed to the vertical tooth surface, which reduces transmission efficiency and increases the thermal deformation at the meshing interface [73, 74]. More so, the flash temperature at the tooth surfaces of gears can be predicted using a nonlinear model, which can estimate the temperature of the tooth overtime that can cause the surface deformation; thus, temperature is suitable for monitoring the performance of the gear, especially when elastohydrodynamic technique is used [75–80]. Thus, it was needful to say that temperature formed a dominant parameter in analysing fatigue failures of gears [81].

4 Conclusion

In the design of power transmissions, the major factors, which affect the system when in application, are noise and vibration emission. The variation in the transmission error distribution has a major impact on the noise behaviour. This study has shown that the noise emission and temperature flash are associated with transmission error due to gear excitation. Further investigation into the material failure of gears, the chemical composition, strength and surface fracture showed that fatigue is one major factor, which usually leads to gear tooth failure. Thus, the outcome of this study can be adopted to improve on the gear tooth design.

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