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A tribo-dynamic contact fatigue model for spur gear pairs

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ABSTRACT

This study proposes a contact fatigue model for spur gears operating under the high speed condition where the dynamic behavior is evident. Realizing the tight relationship between the gear dynamics and the gear tribology, a six degree-of-freedom discrete dynamics model and a mixed elastohydrodynamic lubrication model for spur gears are bridged through an iterative numerical scheme to determine the surface normal pressure and tangential shear under the tribo-dynamic condition, where the gear dynamics and the gear tribology interact. The resultant multi-axial stress fields (from these surface tractions) on and below the surface are then used to assess the fatigue damage. A comparison between the tribo-dynamic and quasi-static life predictions is performed to demonstrate the important role of the gear tribo-dynamics in the fatigue damage. The impacts of the input torque, surface roughness and lubricant temperature on the gear contact fatigue under the tribo-dynamic condition are also investigated.

1. Introduction

The contact fatigue in the form of macro-pitting has been one of the most common failure modes in gearing systems. In both the automotive and aerospace applications, gear pairs often operate within a high speed range, where the gear dynamic behavior is evident and alters the tooth contact force significantly. It has to be noted that the gear dynamics does not play alone. It interacts with the gear tribological behavior, which plays a critical role in the gear contact fatigue [1–7]. Mainly through varying the tooth contact force (The variation of the tooth surface tangential velocity due to the gear dynamic response is usually small in comparison to the kinematic tangential velocity.), the gear dynamics affects the lubrication film thickness, contact pressure and frictional shear [8,9]. The tooth surface frictions that point along the off-line-of-action (OLOA) direction, in turn, produce the main excitations for the OLOA gear vibration, which is coupled with the motion in the line-of-action (LOA) direction by the corresponding frictional moments [9–11]. In addition, the viscous shear occurring in the lubrication film owing to the sliding motion of the tooth surfaces consumes power and provides the gear mesh damping mechanism [12], which is an important component restraining the gear dynamic responses in the vicinity of resonances. These mutual impacts between the gear dynamics and the gear tribology has been commonly referred as the gear tribo-dynamics [9–11]. This study, thus, aims at developing a macro-pitting contact fatigue model that incorporates the influence of the tribo-dynamic behavior for spur gear pairs.

As a gear pair rotates in mesh, the periodic mesh stiffness and the transmission error are the main excitations that dictate the LOA vibrational motion. The alternating number of the tooth pairs in contact and the time-varying compliances (associated with the base rotation, the tooth bending and shear deflections, and the contact deformation) determine the former, and the manufacturing and mounting errors, the intentional micro-geometry modifications, and the deformations due to loading define the latter. A massive number of studies have been carried out focusing on the modeling of the noise and vibration aspect of gears [13,14], using either a discrete lumped-parameter description [8–12,15,16] or a deformable finite element description [17–19]. These works pointed to the significant gear dynamic responses, especially in the vicinity of the resonances. Realizing the important role of the gear dynamic behavior in the lubrication performance of gear contacts, Wang and Cheng [20] evaluated the minimum film thickness under the dynamic loading condition, while assuming Hertzian pressure distributions. Employing the more sophisticated mixed elastohydrodynamic lubrication (EHL) formulation and a two degree-of-freedom (DOF) discrete dynamic description of a general spur gear pair, Li and Kahraman modeled the hydrodynamic film thickness and contact pressure distributions [8] as well as the gear mesh damping [12], demonstrating the tight relationship between the gear dynamics and the gear tribology. Coupling the gear dynamic response and the lubrication behavior in an iterative way, Li [10] and Li and Anisetti [11] examined the mechanical power loss and the flash temperature rise, respectively. Paouris

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et al. [21] incorporated the dynamic load in the sub-surface stress evaluation.

In view of the literature with respect to the contact fatigue considering the dynamic condition, the majority of the studies have been focused on the detection of the failure through the analysis of the dynamic signals in terms of either the vibration [22–28] or the acoustic emission [29,30] induced by the surface pits or wear. Also relying on the vibration analysis, Stander et al. [31] included the fluctuating loading condition in the process of the local fault detection. Besides these experimental works, Choy et al. [32] and Fakhfakh et al. [33] utilized the numerical modeling approach to simulate the gear dynamic behavior caused by the surface fault induced mesh stiffness variation. Regarding the impact of the dynamic behavior (before the occurrence of any surface fault) on the contact fatigue, however, the related works seem to be very limited. For instance, Ramanathan et al. [34] experimentally investigated the influence of vibration on the rolling contact fatigue using eccentric specimens with different hardness levels. It was shown the vibrations indeed promoted the occurrence of surface pitting failure.

Concluding from the literature review above, the theoretical and numerical modeling study on the influence of the gear tribo-dynamics on the gear contact fatigue has been missing. An interdisciplinary model that bridges the gear dynamics, the gear tribology and the contact fatigue fields is required for the appropriate physical description of the gear contact fatigue failure. In this work, a six DOF discrete dynamic formulation [9] is adopted to take into account both the LOA and the OLOA vibratory motions in addition to the torsional vibrations of the gears. The frictional excitations and viscous mesh damping occurring at the tooth meshing interfaces are evaluated using a set of equations that govern the coexistence of the hydrodynamic lubricant flow and the local surface asperity contacts [35,36]. The interaction between the gear dynamic and tribological behaviors is realized through an iterative numerical scheme that couples the dynamics and the lubrication governing equation sets. To determine the multi-axial stress fields on and below the contacting surface, the potential theory based half-space stress formulation [37] is used, provided the normal pressure and tangential shear under the tribo-dynamic condition. A multi-axial fatigue criterion that has been shown to correlate well with a number of contact fatigue experiments [4–6] is then employed to assess the fatigue damage.

This study excludes the gear misalignment [38] and any lead direction crown to allow a uniform load distribution along the axial direction, such that a line contact can be assumed. The thermal behavior that dictates the scuffing failure [11,39,40] is out of the current scope. The surface deflection is confined in the elastic region, assuming the surface hardness is sufficiently high to prevent any plasticity. The modeling of the residual stress production during contact is also excluded. This work deals with the nucleation of the first fatigue crack. Multi-cracks and interactions between cracks are not considered. Because the crack propagation life was shown to be small in comparison to the crack nucleation life for high speed rolling contact fatigue [30,41], this study is limited to the crack formation life prediction. Although the proposed formulation targets spur gears, the methodology is general and can be extended to other types of gears.

2. Formulations

The modeling methodology for the gear contact fatigue under the tribo-dynamic condition is proposed in Fig. 1. A load distribution model [42] that is formulated according to Conry and Seireg [43] is first utilized to perform the tooth contact analysis, and determine the mesh stiffness as well as the static transmission error. Using these excitations, an iterative computational loop consisting of a gear dynamics model and a gear mixed EHL model is then carried out till the convergence of the dynamic mesh force is reached [9]. Under this converged tribo-dynamic condition, the yielded normal pressure and tangential shear serve as the inputs of a stress prediction model to evaluate the multi-axial stress fields, onto which, any residual stress can be superimposed. In this study, the residual stress effect is not considered due to the main focus that is on the tribo-dynamic aspect. Lastly, the fatigue damage is assessed according to a multiaxial fatigue criterion and the material properties that include the tensional and the torsional fatigue strength to determine the contact fatigue crack nucleation life. The details of the load distribution model [42] were fully covered in Refs. [35,43] and are omitted here. The formulations of the other modeling components shown in Fig. 1 are presented as follows.

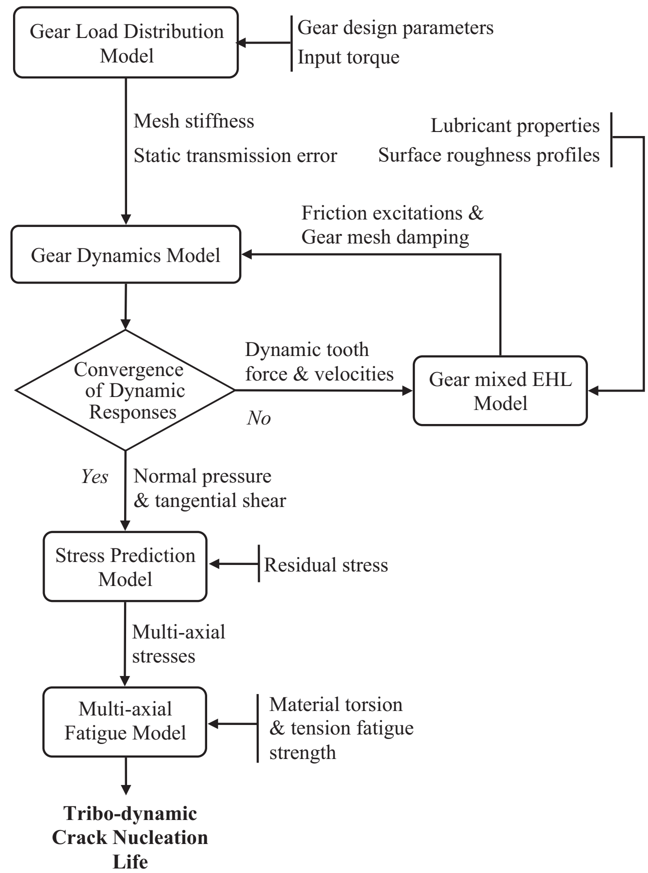

Fig. 1. The modeling methodology for the contact fatigue behavior under the tribo-dynamic condition.

2.1. Gear dynamics model

The six DOF discrete lumped-parameter description as illustrated in Fig. 2(a) is used to simulate the spur gear dynamic behavior. The contact of a general spur gear pair that is composed of gear 1 (driving component) and gear 2 (driven component), whose base radii are r_1 and r_2, respectively, is modeled as two rigid disks with the r_1 and r_2 radii connecting through three elements in series in the LOA direction, representing the gear mesh static transmission error excitation ε_s (manufacturing and mounting errors, micro-geometry modifications, and deformations under loading), the mesh stiffness k_m (alternating number of meshing tooth pairs, and base rotation and elastic deformation compliances), and the