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Research paper

Helical gear wear monitoring: Modelling and experimental validation

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ABSTRACT

Gear tooth surface wear is a common failure mode. It occurs over relatively long periods of service nonetheless, it degrades operating efficiency and leads to other major failures such as excessive tooth removal and catastrophic breakage. To develop accurate wear detection and diagnosis approaches at the early phase of the wear, this paper examines the gear dynamic responses from both experimental and numerical studies with increasing extents of wear on tooth contact surfaces. An experimental test facility comprising of a back-to-back two-stage helical gearbox arrangement was used in a run-to-failure test, in which variable sinusoidal and step increment loads along with variable speeds were applied and gear wear was allowed to progress naturally. A comprehensive dynamic model was also developed to study the influence of surface wear on gear dynamic response, with the inclusion of time-varying stiffness and tooth friction based on elasto-hydrodynamic lubrication (EHL) principles. The model consists of an 18 degree of freedom (DOF) vibration system, which includes the effects of the supporting bearings, driving motor and loading system. It also couples the transverse and torsional motions resulting from time-varying friction forces, time varying mesh stiffness and the excitation of different wear severities. Vibration signatures due to tooth wear severity and frictional excitations were acquired for the parameter determination and the validation of the model with the experimental results. The experimental test and numerical model results show clearly correlated behaviour, over different gear sizes and geometries. The spectral peaks at the meshing frequency components along with their sidebands were used to examine the response patterns due to wear. The paper concludes that the mesh vibration amplitudes of the second and third harmonics as well as the sideband components increase considerably with the extent of wear and hence these can be used as effective features for fault detection and diagnosis.

1. Introduction

Helical gears are commonly employed for power transmissions in a wide range of industrial machines such as wind turbines, helicopters, marine power trains and motor vehicles. As these applications are often of high criticality, condition monitoring of gears has received significant attentions in recent years. Tooth surface wear is a common failure mode of

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transmission systems, that takes place over a long period of service time, it has a negative influence on the dynamic behaviour and vibration response of the gear train [1,2]. The diagnosis of wears as early as possible can avoid catastrophic failures and improve system availability [3–5]. To enable an on-line health monitoring capability, vibration signature analysis has been widely used as an effective tool for machine diagnostic inference.

A wide number of dynamic models for various gearbox systems have been presented in [6–9], in which both torsional and translational vibration responses of gears were studied as a tool for aiding gear fault diagnosis. A variety of models have been developed for the diagnostics of different faults, such as gear spalling or tooth breakage [7,10–12], tooth crack [13–16], shaft misalignment [17,18], tooth surface pitting and wear [19–24]. More models have been developed to analyse the time varying mesh stiffness in a helical gear [25–29] and to study the effect of parametrical design on the dynamic behaviour of helical gear system [30–33]. Numerical models can be very valuable for gaining in-depth understanding of the complex interaction between transmission components, whereby effective methods to process vibration signals for implementing accurate and reliable diagnostics can be developed. However, few models have been presented for fault detection and diagnosis in helical gear systems, likely due to the increased complexity of time-varying contact lines during the meshing process.

Several studies have been performed to develop analytical methods for modelling helical gear stiffness. Kar and Mohanty [34,35] suggested an algorithm for determination of the time-varying stiffness, time varying frictional force and torque between meshing teeth and the bearings in a helical gear system. This algorithm was revised and refined by Jiang et al. [36–38] to develop more accurate representations in stiffness variations of helical gears during the mesh process. They investigated the effect of spalling defect, tooth breakage and mesh misalignment on the helical gear dynamic features. Chang Q. et al. [39] used the same algorithm to develop a dimensionless method for studying the nonlinear characteristics of helical gear model. Mączak [40] presented a simulation model based on finite element method (FEM), for detection of local faults like pitting and tooth fracture in helical gears using abnormalities in the time vibration signal, whereas long computation time is required with FEM. A number of dynamic models of spur and helical gear systems incorporated with a wear formulation were studied by Ding [20,41], in terms of gear design modifications. However, more accurate models are needed to investigate the wear effect on helical gear dynamic performance for easier demonstrating and evaluating the condition monitoring perspective.

Numerous dynamic models of gear systems were incorporated with a generalized wear formulation to predict the interactions between the dynamic behaviour and tooth surface wear [20]. A family of dynamic models of spur and helical gear systems incorporated with a wear formulation based on Archard's wear model [21,23,42–47] due to its simplicity, however it requires an experimental wear coefficient which is difficult to be determined as it depends on many aspects such as material properties, lubricants, surface quality, operating conditions [23]. In dynamic respect, the wear effect is mainly characterized by loss of tooth profile that represented by modulated mesh excitations [20,24,48], to investigate the effects of surface wear on system's dynamic characteristics. They indicated that tooth surface wear and gear dynamics are highly interacted, whereas tooth wear may cause unfavourable changes in the tooth surface topography and have a significant adverse effect on gear life and performance. However, limited number of contributions has been reported to include the combined influence of wear evolutions and vibrations for helical gears with respective to accuracy and easiness of implementation for condition monitoring and diagnostics for the early stages of wear. In addition, monitoring of gear wear based on vibration is not particularly well-established [49] and most of the models either ignore or assume constant frictional effects, which is likely to be very different from real applications where the load and hence the frictional forces vary during the meshing process.

Various models have been produced to evaluate the effect of sliding friction on spur and helical gear dynamic responses [50], based on FEM [51–53] and numerical modelling [54], using different values of the coefficient of friction. These have indicated that friction appears as a non-negligible excitation source, which can generate significant time-varying excitations and enhance the amplitudes of the lower and higher harmonics of the translational responses, which in turn can enhance conventional diagnostic features [55]. To date, few studies have focused on the diagnostics of tooth surface wear with the inclusion of frictional effects and most of the presented helical gear models have not been validated with the experimental work.

The main objective of this study is to develop a computationally efficient and stable analysis of the dynamic response of a helical gearbox for the purpose of condition monitoring. To this end, a numerical model is developed to simulate time-varying mesh stiffness, coupled with EHL frictional model and tooth wear characteristics, as a basis for increasing the accuracy of gear diagnostics by examining the changes in dynamic forces and the corresponding vibration responses under different degrees of tooth surface wear. The results obtained from the model are then validated by vibrations acquired from a run-to-failure experimental approach. As a result, an accurate diagnostic model is presented to define effective indicator features of tooth surface wear defects.

2. Modelling tooth wear in helical gears

Gear wear results in deviation from gear tooth profile and thickness as well as altering load distributions and contact stresses, which can accelerate the occurrence of other failure modes such as pitting and scoring [20,56]. Stiffness reduction is commonly used in dynamic gear mesh models to represent tooth surface defects [19,57,58].

Tooth surface wear can cause sliding and the normal load amplitudes to vary with the position of the contact on the tooth surfaces, in turn this can cause difficulties with the computation of load distributions for the gears [59]. Wear tends