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The influence of tooth pitting on the mesh stiffness of a pair of external spur gears

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ABSTRACT

Time-varying mesh stiffness is one of the main internal excitations of gear dynamics. With the growth of gear tooth fault, like pitting, cracking and spalling, the mesh stiffness amplitude changes and consequently the dynamic properties of the gear system change. This study is devoted to deriving equations of the mesh stiffness of a pair of external spur gears with tooth pitting. Different pitting severity levels are modeled. The influence of tooth pitting on the gear mesh stiffness is investigated. The relationship between pitting severity and mesh stiffness is established. The proposed method is validated to be effective in mesh stiffness evaluation by comparing with a finite element model.

1. Introduction

Due to high service load, harsh operating conditions or fatigue, faults may develop in gears [1]. Gear faults are responsible for approximately 60% of gearbox failures [2]. Most of these come from damage on the gear teeth such as pitting, cracking, and spalling [2]. Through observations at Syncrude Canada Ltd, fatigue crack and tooth pitting were the two commonest failure modes [3]. Crack is a non-lubrication-related failure mode while pitting is a lubrication-related failure mode [2]. Many researchers modeled gear crack and its effect on gear mesh stiffness [4]. However, the research on gear tooth pitting modeling and its effect on gear mesh stiffness is limited. This study focuses on gear tooth pitting modeling and investigation of its effect on the time-varying mesh stiffness of a pair of external spur gear.

According to American Society for Metals (ASM) handbook [5], "Pitting occurs when fatigue cracks are initiated on the tooth surface or just below the surface. Usually, pits are the result of surface cracks caused by metal-to-metal contact of asperities or defects due to low lubricant film thickness. High-speed gears with smooth surfaces and good film thickness may experience pitting due to subsurface cracks. These cracks may start at inclusions in the gear materials, which act as stress concentrations, and propagate below and parallel to the tooth surface. Pits are formed when these cracks break through the tooth surface and cause material separation. When several pits join, a larger pit (or spall) is formed. Pitting can also be caused by foreign particle contamination of lubricant. These particles create surface stress concentration points that reduce lubricant film thickness and promote pitting."

Tan et al. [6] experimentally measured pitting growth under different levels of load. In order to create surface pitting in a relatively short time frame, lubricant oil (SAE 20W-50) without anti-wear properties was employed. The experimental tests were performed at a rotational speed of 745 rpm but under different torque levels: 220 N m, 147 N m, and 73 N m. For the higher applied

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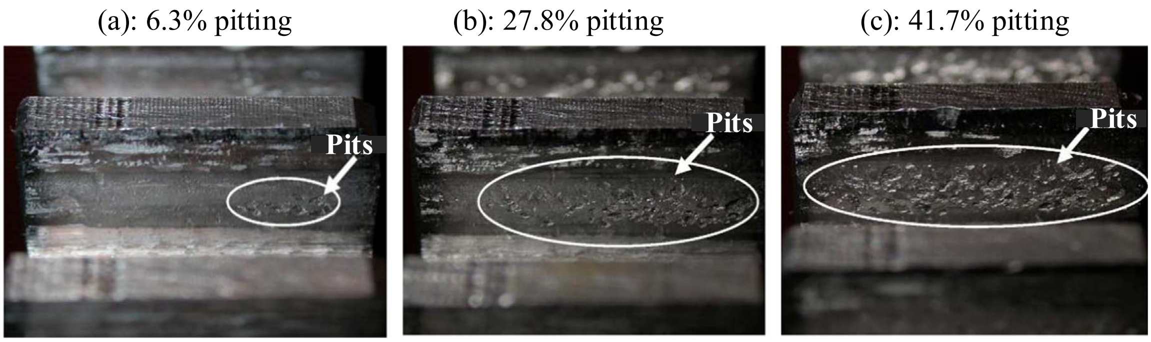

Fig. 1. Pitting growth under the operation condition of 73 N m and 745 rpm [6].

torque conditions (220 N m and 147 N m), pitting occurred across the face width and was evident on most of the gear teeth. For the lower applied torque condition (73 N m), pitting was spread across the face width of the gear teeth at a much slower rate and was localized to only a few teeth. Prolonged operation time resulted in pitting spreading to other gear teeth. Fig. 1 shows the pitted area progression from 6.3% to 41.7% of the gear tooth surface, under the test condition of 73 N m and 745 rpm.

Man-made pitting was produced on gear teeth by several researchers to experimentally explore its corresponding fault symptoms of a gearbox. Gelman et al. [7] artificially etched grooves along the pitch line of a single tooth to mimic pitting fault. Lee et al. [8] created a pit on tooth surface at around the pitch line by removing a small part of the tooth material. Combet et al. [9] manually produced pits on the tooth flank of five teeth. The pitted teeth were not adjacent to each other, but separated by six healthy teeth. Öztürk et al. [10] first created circular pits on one tooth using electro-erosion machine. Then more pits with the same size were added to that tooth and also some were created on neighboring teeth to account for pitting growth. Hoseini et al. [11] artificially created circular pits on a planet gear using the electro discharge machining in their planetary gearbox experimental tests. The number of pits was varied to mimic the slight, moderate and severe pitting damages as shown in Fig. 2. In this study, we also model the gear tooth pitting using circular pits as did in [10,11].

Several researchers investigated the effect of a single pit or a spall on the time-varying mesh stiffness of gears. Chaari et al. [12] and Choy et al. [13] roughly modified the shape of gear mesh stiffness to simulate the pitting fault. They did not provide any principle or equation to determine the gear mesh stiffness with pitting growth. Cheng et al. [14], Abouel-seoud et al. [15] and Chaari et al. [1] analytically studied the effect of a single pit on the time-varying mesh stiffness of gears. The pit was modeled as a rectangular shape as shown in Fig. 3(a). In Cheng's model, the pitting length (a) and pitting width (b) were fixed while the pitting severity was determined by the pitting depth (c). In Abouel-seoud's model, the pitting width (b) and pitting depth (c) were fixed while the pitting severity was determined by pitting length (a). Chaari et al. [1] developed two models in his study. One is the same as Cheng's model [14] while the other one is the same as Abouel-seoud's model [15]. Rincon et al. [16] evaluated the pitting effect on the time-varying mesh stiffness of a pair of gears using the finite element method. A single pit was modeled in elliptical shape as shown in Fig. 3(b). The pit size was fixed but pitting location's effect on gear mesh stiffness was investigated. Three pitting locations were investigated, respectively, namely single tooth contact zone, double-tooth contact zone, and transitional zone from single to double contact. Ma et al. [17] investigated the effect of tooth spalling on gear mesh stiffness. A single rectangular spalling was modeled and the effects of spalling width, spalling length and spalling location on stiffness were investigated, respectively. All the above studies regarding gear mesh stiffness evaluation focus on a single tooth pit. Their methods cannot be used to evaluate the mesh

Fig. 2. Planet gears with artificially created pitting damage [11].