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In situ surface characterization of running-in of involute gears

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ABSTRACT

Gear life and operation are largely determined by the properties of the contacting surfaces, which inevitably change over the gear life. The initial topography transformation, a characteristic effect of running-in, is very important. This paper focuses on how the running-in of the surface topography can be characterized and what methodology can be used for this purpose. To characterize running-in, gears were run in an FZG back-to-back test rig and the changes in surface topography were measured in situ using a Form Talysurf Intra. This enables the same gear tooth surface to be measured with enough precision to follow its development through the different stages of running-in. Gear tooth surfaces as manufactured were measured on three occasions: in initial manufactured condition, after a standard running-in procedure, and after an efficiency test. Running-in was characterized both qualitatively by plotting roughness profiles and quantitatively by analyzing a selected set of roughness parameters. This paper demonstrates that: the asperity peaks were worn off in the initial running-in stage; roughness, waviness, and form can be separated using a carefully chosen polynomial fit and the Gaussian filter; surface topography can be examined initially, after running-in, and after operation in situ; and complete wear of the initial surface can be observed in specific circumstances.

1. Introduction

Gears are among the most highly loaded machine elements, subject to continuous sliding and rolling contact. The contact loading of the gear surfaces needs to be carefully designed based on the application requirements for life and performance. One key parameter for gear performance and life is the gear surface topography. The initial gear surface state as manufactured changes during the running-in phase. Hence, careful characterization and prediction of the gear surface evolution from the initial state, through the running-in phase, and during operation is important.

One of the earliest studies of the running-in of gear surfaces was conducted by Andersson [1,2]. In the case of hobbed gears, Andersson stated that a running-in period of 300,000 cycles reduced the surface roughness amplitude by 7–16%. Flodin [3], using both optical and stylus measurement instruments, concluded that wear occurred primarily near the tooth root and tip, and described the initial wear rate as very high. Sjöberg et al. [4] studied running-in by focusing on the manufacturing methods. They combined surface roughness measurements with contact simulations and concluded that the manufacturing methods drastically changed the real contact area ratio and hence the running-in of the gear surfaces. Bajpai et al. [5] simulated gear form wear by combining Vijayakar's wear model [6] with Archard's wear law, finding good correlation between experimental and simulated results. Other running-in studies focus on simpler rolling–sliding geometries, for example, that of two rollers in contact. This simplifies the problem of differentiating between form, waviness and roughness for the involute gear profile. Khonsari and Akbarzadeh [7–9]simulated and tested rollers under different conditions to mimic gear tooth contact in order to predict running-in. They found a good correlation between simulated and measured running-in in terms of form wear and prediction of the arithmetic roughness amplitude parameter, R_a. No method for studying the surface transformation during the running-in process of gears has been published.

Furthermore, several authors have studied this phenomenon from different points of view. Blau, for example, defines running in (no hyphen) as the process to intentionally induce surface change in order to improve the life of the contacting surfaces. [10]. Additionally to this definition, Johnson points out that running-in has a wear component, but also has a plastic deformation component when dealing with rough contacts [11]. On the observation of running-in, Bengtsson and Rönnberg study and measure running-in in a reciprocating tribometer [12]. To study the effect of surface roughness and waviness in a conformal contact, Wu and Zheng test conformal contact between rough surfaces and conclude that running-in does not change the waviness of the surfaces [13]. Bosman et al. simulate the running-in process for a purely sliding, rolling and rolling sliding contact respectively [14–16]. All these studies either simulate, experiment or study running-in in a general sense; however, there is a lack of a clear running-in description and observation during a gear mesh.

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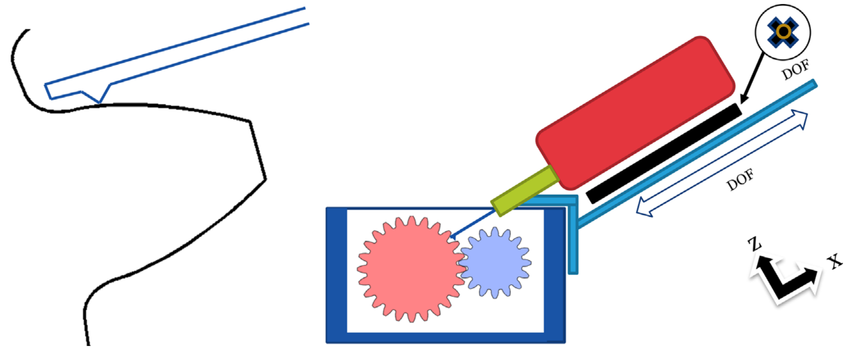

Fig. 1. Left schematic of gear tooth measurement; Right, schematic surface roughness instrument in situ as well as degrees of freedom.

This study presents an in situ methodology for characterizing and quantifying surface transformation during running-in in an FZG back-to-back test rig.

2. In situ surface characterization methodology

2.1. Test equipment and repositioning

The surface transformation measurement and transformation analysis methodology was designed for the FZG back-to-back test rig [17] at the Department of Machine Design, KTH Royal Institute of Technology.

In this method, the surface topography is measured using a Form Talysurf Intra manufactured by Taylor Hobson [18], mounted directly on the test gearbox as shown in Fig. 1. This instrument has a resolution of 16 nm over a 1-mm height range. Measuring the surface topography in situ enables the surface topography to be inspected without disassembling the test gearbox, and hence changing system parameters that might affect subsequent test results. Surface roughness was measured for 6 mm along the wheel profile near the start of the active profile. In this setup, only the wheel on the test gearbox can be measured due to physical space constraints. A positioning stage is used below the profilometer. This enables profiles to be measured along the lead of the tooth (see Fig. 1). Note that the surface roughness measurements are made using a contact profilometer without a skid, enabling the determination of form, waviness, and roughness.

The profilometer's overall positioning has two degrees of freedom: positioning stage displacement (in the y direction) and linear motion (with a linear guide) along an oblique angle situated on the x–z plane. These two degrees of freedom (see Fig. 1) allow the profilometer to be positioned to measure any part of the flank.

To reposition the profilometer in the same position, specific fixtures are used. To position the profilometer in the profile direction, a spirit level is placed on top of two specific teeth of the wheel; the spirit level used has an accuracy of ± 15 min of an arc. If the surface lay is exceedingly directional along the lead, as in the case of ground surfaces, the method described in Section 3 is helpful for positioning two profiles in the exact same place.

To accurately position the profilometer with reference to the gearbox, two shallow 3-mm pinholes are drilled into the top cover of the gearbox. The positioning stage, shown in Fig. 1 as a black rectangle is used to measure several profiles and then stitch the profiles together to form a surface. This device has an accuracy of $\pm 5\ \mu$m.

To perform a running-in analysis of the in situ-measured gear tooth surface roughness, several steps need to be performed, as illustrated in Fig. 2. A polynomial fit is used to extract the form, after which a Gaussian filter is used to extract the waviness from the surface roughness.

The involute is a mathematically complicated form to extract from a measurement, as it includes both waviness and roughness.

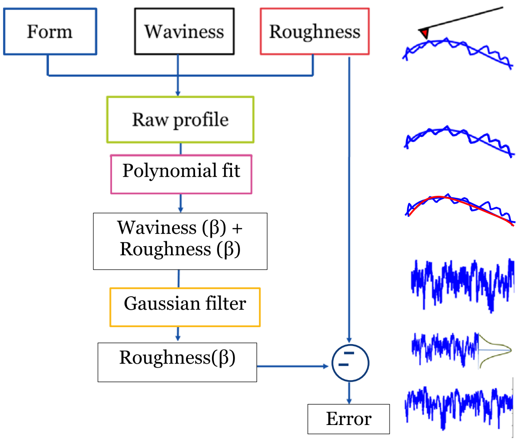

Fig. 2. Method to determine the surface roughness of an in situ measured gear tooth.

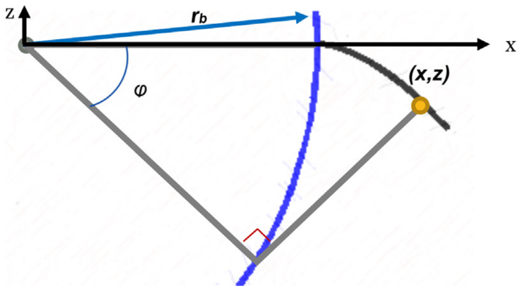

Fig. 3. Involute function plot.

The approach used here is to represent the form of the tooth using a polynomial fit along the profile direction.

To verify this method, an involute was generated based on the following equations:

$$x = r_b(\cos(\varphi) + \varphi \sin(\varphi)) \tag{1}$$

$$z = -r_b(\sin(\varphi) - \varphi \cos(\varphi)) \tag{2}$$

The parameter r_b is defined as the base circle radius and φ is defined as the roll angle, shown in Fig. 3.

To achieve constant step values in x, Δx is fixed, then the nonlinear eq. 1 is solved for φ. The resulting values of φ are subsequently used to solve for z. After obtaining this curve, different waviness waves and roughness waves having the same values of x_i are superimposed onto the involute based on Eqs. (1) and (2). To generate deviations in the involute, in the form of waviness and roughness, the following