

Monitoring the Progression of Micro-Pitting in Spur Geared Transmission Systems Using Online Health Monitoring Techniques

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ABSTRACT

Micro-pitting is a fatigue effect that occurs in geared transmission systems due to high contact stress, and monitoring its progression is vital to prevent the eventual failure of the tooth flank. Parameter signature analysis has been successfully used to monitor bending fatigue failure and advanced phases of gear surface fatigue failure such as macro-pitting and scuffing. However, due to modern improvements in steel production the main cause of gear contact fatigue failure can be attributed to surface micro-pitting rather than sub-surface phenomena. Responding to the consequent demand to detect and monitor the progression of micro-pitting, this study experimentally evaluated the development of micro-pitting in spur gears using vibration and oil debris analysis. The paper presents the development of an online health monitoring system for use with back-to-back gear test rigs. The results validate the system capabilities in detecting early gear defects and reliably identifying the type of failure so that it can be used in predictive health monitoring (PHM) systems.

KEY WORDS

Transmissions, Spur Gears, Predictive Health Monitoring, Micro-pitting, Surface Fatigue, Vibration Analysis, Online Oil Debris Analysis

INTRODUCTION

Pitting is one of the main failure mechanisms in gears. It occurs as a result of a high level of Hertzian contact stress

that the surface cannot withstand. Smith [1] explained two ways in which pitting develops: initial (micro) pitting and progressive (macro) pitting. During the running-in period, asperities are removed and small pits are created which allow for better load redistribution, while macro-pitting occurs when the load distribution associated with micro-pitting is not sufficient to reduce contact stress below the fatigue limit. This leads to the initiation and removal of further pits [1]. To prevent an unexpected failure due to the progression of localised defects it is necessary to monitor the initiation and progression of pitting. Three monitoring techniques are currently used in gear transmission systems in order to improve maintenance scheduling and reduce failures involving the analysis of vibration, acoustic emissions and oil debris. Researchers have studied these techniques to establish which is most capable of tracing and classifying fault occurrence and predicting the onset of failure. Such studies have produced a range of results highlighting various advantages of the different techniques. However, only a few considered surface contact failure. Furthermore, many studies have been based on artificially induced gear faults and not on natural degradation failures. The present authors have investigated both bending and surface contact fatigue failures in helical gears [2, 3, 4, 5, 6], and this study builds on previous research to investigate the monitoring of spur gears.

Vibration monitoring can be used to acquire information about transmission components under normal operating conditions that would otherwise be inaccessible. Several studies have presented the application of time domain analysis (TDA) methods in order to recognise gear defects [7,

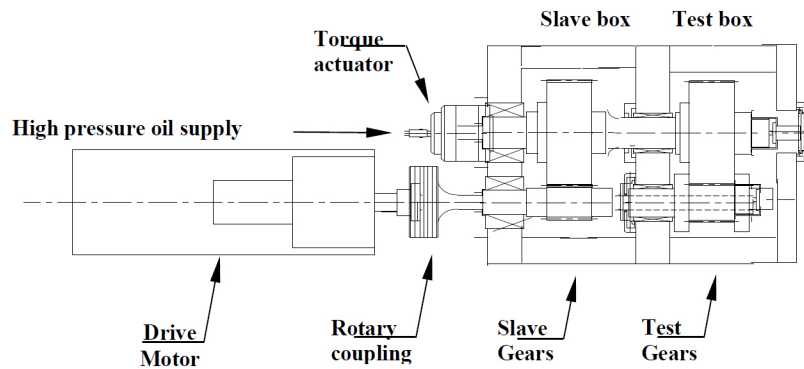


Figure 1. Newcastle University 75 mm centre distance back-to-back gear test rig

8, 9, 10, 11, 12, 13]. By analysing statistical information from vibration signals, the average overall vibration level can be used to set acceptance limits. Samuel and Pines [10] have reviewed different TDA diagnostic methods applied to vibration. Tan et al. [11,12] exploited TDA statistical information extracted from vibration signals to monitor pitting in spur gears. However, in both of these studies the authors concluded that using vibration RMS level as an indicator of gear pitting rate was less satisfactory than other monitoring techniques. Many other studies have used TDA to extract useful information from vibration signals, but most either did not focus on micro-pitting or adopted advanced mathematical techniques to extract useful information contained in the vibration signal.

During the operation of power transmission systems, wear debris is generated and transported by the oil. The identification and classification of this debris can help to understand the wear mechanism and relate it to a specific wear process. Oil debris analysis (ODA) can be used to determine whether or not the transmission requires maintenance and it can serve as a prognostic indicator in power transmission system health monitoring [14]. Different approaches have been used to analyse and classify wear debris. Flanagan et al. [15] presented the two main approaches used in ODA; lubricant sampling analysis and direct detection analysis. The lubricant sampling approach is based on the periodic analysis of oil samples to check concentrations of debris particles, whereas direct detection analysis provides online information about debris in the oil using a sensor that can detect the presence of wear particles.

The effectiveness of acoustic emission, vibration, and ODA monitoring was experimentally investigated in [11,12,18, and 19]. The authors concluded that the vibration analysis and ODA results did not offer earlier indications of gear damage in comparison to AE RMS monitoring. Several experimental investigations have explored combined techniques monitoring AE, vibration and oil debris to study the ability to predict the condition of helical geared transmission systems whilst conducting fatigue tests that allow gear pitting to occur

under normal running conditions, using intelligent approaches [2, 3, 4, 5, 6]. The authors concluded that all three techniques (acoustic emission, vibration analysis and ODA) not only offer an earlier indication of gear damage, but can also predict the onset of failure which enhances the results concluded [11,12,18, and 19] for the spur gears transmission system investigated.

EXPERIMENTAL TEST RIG

An existing back-to-back gear test rig based at Newcastle University was used for this research. The rig comprises a 75 mm centre distance back-to-back test gearbox connected to a slave gearbox in a layout shown in Figure 1. The test gears, each consisting of a pinion and a wheel, are lubricated by a pressurised spray of Atlas Copco Roto Z lubrication oil, pumped from a 60 litre tank located beneath the rig bed. In order to ensure that the lubrication oil fed to the gearbox is free of particles, it is passed through a 125µm suction filter, a magnetic filter and two 10µm filters (Maxiflow MX. 1518.4.10) before reaching the gears. The used oil from the test gearbox is returned to the tank by gravity through a return pipe. Separate systems provide lubrication for the slave gearbox and bearings.

The system is driven by a 5.5kW variable speed electric motor controlled by an inverter to provide a speed variation of 0-6000 rpm. Testing torque is generated through a hydraulic mechanism and a slave gearbox is used to apply the load. The rig can generate a load torque on the test gears in the range of 0-600 Nm. The torque is measured using calibrated strain gauges installed on the wheel shaft and the measured torque values are transmitted to the control program by telemetry in order to provide closed loop torque control of the actual load on the gear itself. The test rig, as shown in Figure 2, is controlled using National Instruments (NI) LabVIEW which consists of a PCI-MIO-16E-4 E series data acquisition card (NI) with 16 channels and sampling rate of 250ksps. Temperature is monitored using a USB-9211A temperature data acquisition card (NI). Three oil heaters and a water cooler are used to ensure that the running oil is maintained at a constant temperature during the tests.



Figure 2. The 75 mm centre distance back-to-back gearbox

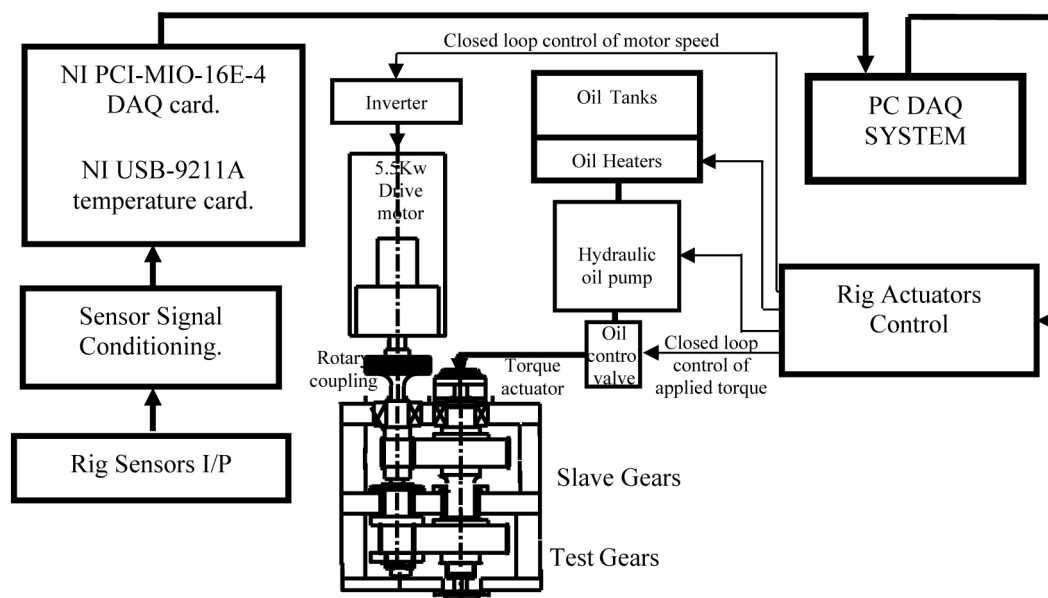


Figure 3. 75 mm test rig sensor-actuation system layout

Temperatures were measured at four locations; rig bulk oil, test gear bearing and slave gear bearing. Oil pressure and flow rates were also measured. A gear tooth trigger sensor was installed adjacent to the pinion test gear to ensure that tooth failure could be recorded. The input shaft speed and motor current were also monitored as a precaution. The test rig software provided the flexibility to change the control algorithm of the parameters measured according to the test conditions using LabVIEW's scalable architecture features. The test rig sensor-actuation system layout is shown in [Figure 3](#).

A pair of spur gears was tested under closely controlled conditions. The gears were made of OVAKO 157C carburising steel with the case hardened to a surface hardness of 650-750 Hv. The test gears were 4.2 mm module spur

gears with a 14/21 gear ratio and a 10 mm nominal contact width. The gears were surface ground and manufactured to grade 5 (ISO 1328). The basic geometric specifications for the spur gears under test are provided in [Table 1](#).

Table 1. Basic geometry of test gears

Specifications	Gears Under Test	
	Pinion	Wheel
Module (mm)	4.2	
Gear Centres (mm)	75	
Number of teeth	14	21
Face Width (mm)	10	15

ONLINE HEALTH MONITORING TECHNIQUES

A power transmission health monitoring system (HMS) has been developed and is currently being validated to recognise failures, including gear surface failure by micro-pitting. The system was developed for trend monitoring to show how parameters change from a base line signature. The system monitors vibration and oil debris. Various methods can be used to analyse vibration, such as time domain analysis (TDA), frequency domain and time-frequency domain analysis. This paper focuses on investigating the capabilities of TDA methods in detecting the progression of pitting and the measurements of the three parameters are compared. Subsequent publications will focus on presenting the capabilities of the HMS and the different analytic techniques. The system is capable of online monitoring, automatic measurement and analysis and any changes in gear condition and its degradation during operation can also be identified. The test rig design information is important to the HMS and at running speed, all the necessary information for frequency analysis is automatically calculated and presented. The advantage of developing vibration analysis and ODA tools arises from the requirement to enhance online analysis methods according to the needs of each study.

The application of TDA to vibration signals is usually performed by means of time domain averaging and then the statistical characteristics of the wave forms acquired are extracted, including their mean, variance, root mean square (RMS), and kurtosis. This allows the extraction of the key features of a time series signal. In this study TDA monitoring methods were used to extract RMS and kurtosis parameters as follows:

The RMS, defined as “the square root of the average of the sum of the squares of the signal samples”, is given by [equation \(1\)](#):

$$RMS_x = \sqrt{\frac{1}{N} \left[\sum_{i=1}^N (X_i)^2 \right]} \quad (1)$$

where X is the original time signal sampled, N is the number of samples and i is the sample index [10].

The kurtosis function (Ku) provides a measure of the higher-order statistical attributes of a time series, and is defined as “the fourth normalized moment of a given signal X ” [10], as given by [equation \(2\)](#):

$$Ku = \frac{N \sum_{i=1}^N \left(x_i - \bar{x} \right)^4}{\left[\sum_{i=1}^N \left(x_i - \bar{x} \right)^2 \right]^2} \quad (2)$$

Kurtosis can measure the ‘peakedness’ of the time series signal (TSS). A TSS with relatively sharp peaks may have a kurtosis greater than three, whereas a TSS with relatively flat peaks will have a kurtosis of less than three. Kurtosis can also be used to characterise the impulsive character patterns using different frequency bands, due to its high response to the distribution of peaks [17]. Braun [17] suggested that a kurtosis value close to three can be an indication of a healthy machine, whereas higher values can possibly indicate a developing defect.

The vibration monitoring system incorporated a DSA PCI-4772 24-bit data acquisition card (NI). The signals were acquired by two DJB Piezotronic constant current source accelerometers (model no. A/120/V) mounted adjacent to the test gear bearings transversely to the gearbox casing and a shaft speed sensor was used to acquire the shaft rotation reference. Data was acquired at 25.6ksps continuously and a block of 6000 samples were logged every minute.

Metallic debris in oil generated by surface fatigue in the forms of micro-pitting, macro pitting, and gear scuffing was collected. The on-line debris analysis system is based on a direct measurement principle using a particle counting sensor and a total ferrous sensor from ANALEXrs provided by Kittiwake. The ANALEXrs particle sensor was fitted in the oil return pipe to detect wear debris from the running gears as shown in [Figure 4](#). All used oil from the test gearbox passed through the internal bore of the sensor. Readings from the sensor relate to ferrous and non-ferrous particles ranging in size from 40 to over 300 μm and subsequent calculations were given of total mass of particles/hr, total particles in all size ranges, and particle rate/min. The date, time and number of cycles of the pinion shaft relating to each reading were also logged. The sensor was able to count ferrous and non-ferrous debris and classify it into different particle size ranges. The counting process is shown in [Figure 5](#). The ODA software was developed using LabVIEW, which communicates with the sensor using an RS232 serial port interface operating at 57.6kbaud. The sensor updates the measurement readings every 10s and the software classifies the different particle sizes and presents instantaneous data readings as well as test data trends for both ferrous and non-ferrous debris. Instantaneous data readings were logged using two data formats: with and without time stamp. The logged data without a time stamp was used for instantaneous on-line data analysis, whilst the time-stamped data was used for

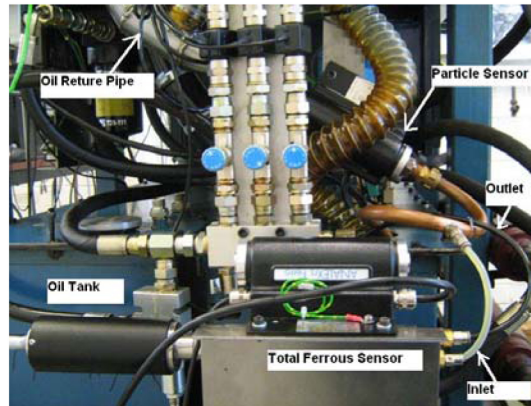


Figure 4. Particle and total ferrous sensors, mounting positions

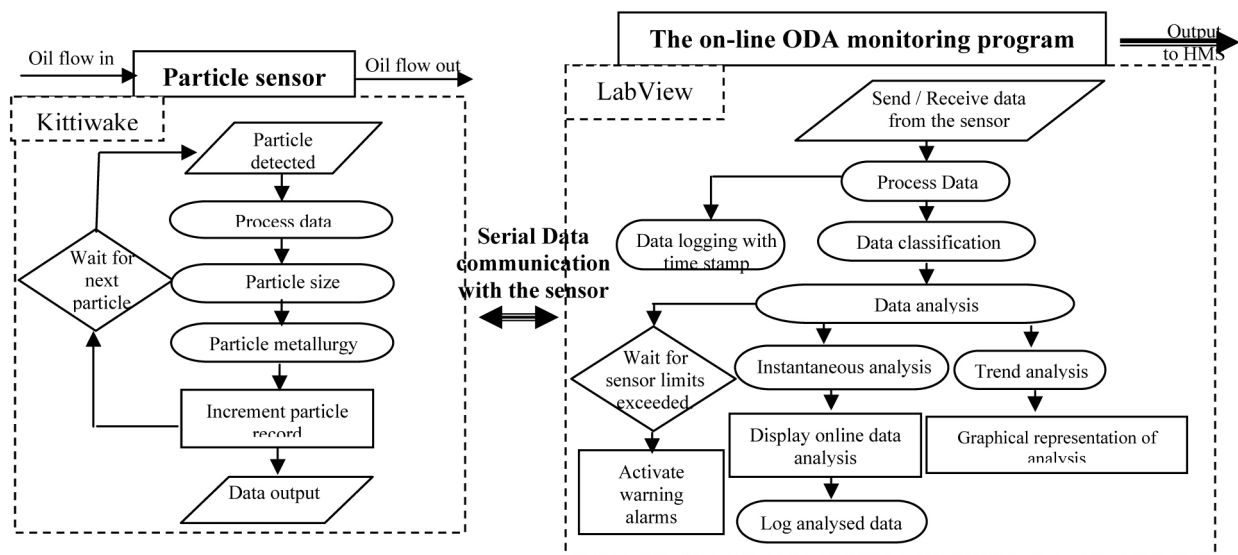


Figure 5. Particle sensor counting process and the algorithm of the ODA monitoring program

further data analysis and processing. The total ferrous sensor (second sensor) was used to detect the content of ferrous particles in the used oil. Oil was sampled from a pipe connected to the outlet end of the particle sensor. The pipe served as an oil collector between the particle sensor and the tank. The sampling position was chosen so that oil would always be away from the bottom of the pipe, thus free from sludge. The body of the total ferrous sensor was positioned below the oil level of the pipe, mounted separate from the structure of the rig in order to isolate vibration. The readings of the total ferrous sensor include values in ppm and time in seconds since the sensor was switched on and these were logged through the RS232 connection to a NI LabVIEW based programme at a rate of 1S/1.5 min. The date and time relating to each reading were also logged.

EXPERIMENTAL TESTING

The experimental testing aimed to investigate the ability of vibration monitoring and ODA to assess the progression of micro-pitting under normal running conditions. It was designed to ensure the progression of natural micro-pitting during the testing schedule as shown in Table 2. All test run conditions were carried out at a constant oil temperature of 60°C. Several confidence tests were carried out after the initial installation of the particle sensor, such as verifying the effect of changing oil temperature and flow rate on the sensor reading. No drift of sensor readings due to changes of either oil temperature or oil flow rate were observed. Also, a confidence test for the oil system and the particle sensor was carried out by circulating the oil through the sensor, without gear rotation, at a temperature of 60°C and flow rate of 3.2l/min. The purpose of this was to investigate the stability of the sensor and to monitor the background oil condition before testing with gears. The oil was circulated for 12 hours and no