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Towards real time automated early gear failure detection

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ABSTRACT

The ability to stop a gear fatigue test before catastrophic failure has many advantages. However, today, a widely accepted approach is not available. This case study applies a vibration-based condition monitoring methodology to detect early gear failures. The gear studied takes part in an all-wheel-drive drivetrain system. Vibration signals from four run-to-failure fatigue tests at two constant torque-speed combinations were used as input to time-synchronous averaging and autoregression model generation. The applied methodology shows promising results for early failure detection, and the process is feasible for implementation in an automated environment. Real time analysis is also possible since the autoregression model generates a healthy state TSA signal during the early testing stages. However, the time to failure detection varies with operating conditions, with low sensitivity at high-speed and low-torque conditions.

1. Introduction

Experimental testing is needed to verify models. This study aims to improve testing efficiency by stopping it in time. Ideally, test termination should occur for gear components when a single tooth has either a sizable crack or a single tooth breakage, according to Hong et al. [1]. They further state that gear literature is sparse in rotating gear tooth bending experiments because reliable diagnostic methods to stop the test before catastrophic failure occurs are lacking. Most prior research in condition monitoring of gears focuses on applications such as the health monitoring of drivetrains for helicopters. However, early failure detection in rigs has unique requirements. Firstly, the technique should enable automatic shutdown as fatigue tests last a long time. This means that the output of any technique should be a quantifiable metric, with which a threshold can be set to initiate the shutdown. Secondly, it should be capable of analysis in real-time. Thirdly, it should be robust to changing conditions of torque and speed.

Hong et al. [1] implement a vibration-based methodology where an adaptive upper threshold for vibration Root Mean Square (RMS) is used as a criterion to stop the fatigue test. However, simple statistical metrics such as the RMS do not offer reliable detection capabilities, as they are susceptible to changing operating conditions and random disturbances. Antoni and Randall [2] developed a method to extract useful information from vibrations using spectral kurtosis to detect and characterise early faults that produce impulse-like signals. Their approach enabled determining the range of frequencies of interest for a specific fault. However, their process would require test engineers to check the spectral kurtosis continuously. Wang and Wong [3] developed a methodology based on the concepts of Time Synchronous Averaging (TSA) and Autoregression (AR) modelling to monitor helicopter drivetrain health. They implemented the method on real gearbox vibration signals and claimed early failure detection. This methodology was later used for another gear application by Wändell [4] to automate real-time quality control in gearbox production lines without expert human interpretation.

This study applies the methodology based on TSA and AR modelling concepts proven useful by [2,4] to detect early failures. One difference is that referred work uses simulated and real vibration signals; our work applies only real signals. This study aims to increase the knowledge gained from fatigue testing of an all-wheel-drive drivetrain subassembly named Rear Drive Unit (RDU), Figure 1, by enabling test termination at an early stage. The RDU receives power from the transmission and splits it between the rear wheels. The RDU contains a hypoid pinion and ring gear.

2. Method

The test setup for gear fatigue testing of the RDU was a back-to-back gear test rig. The RDU is the test gearbox, while the Slave RDU acts as the reaction gearbox.

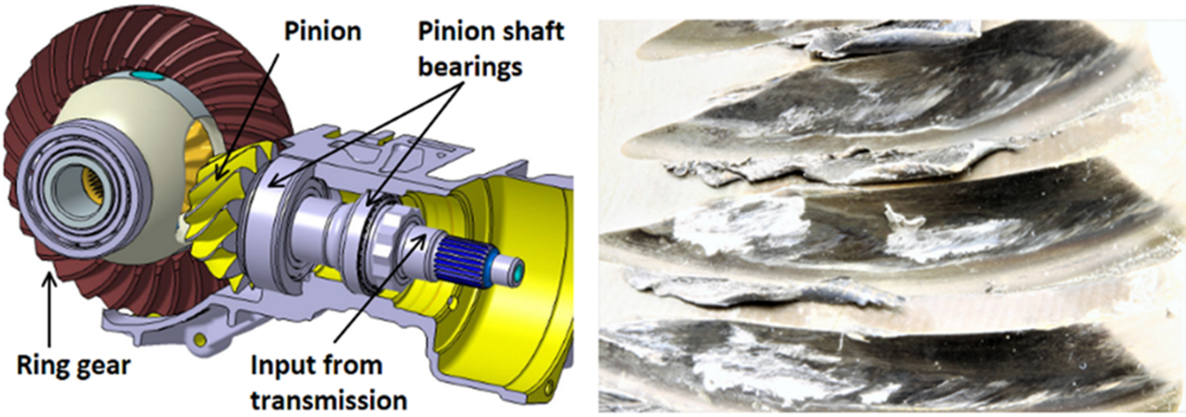

Figure 1. Illustration of a Rear Drive Unit (left) and a photo after a catastrophic failure of the gear.

A piezoelectric accelerometer was mounted on the RDU casing, close to the pinion bearing. The accelerometer connects to a frontend, a device that performs pre-processing such as anti-aliasing and analogue to digital conversion. We assumed the ideal rpm during signal processing as the real test rig rpm closely followed the ideal rpm with an error of ±0.5 rpm. Therefore, signal analysis was carried out after the tests concluded and not in real time.

Fatigue tests were carried out at two torque-speed combinations 1500 Nm at 850 rpm and 640 Nm at 1200 rpm, with two repetitions for each combination. The interval of signal recording was decided based on the expected lifetime of the RDU undergoing the fatigue test. High-torque tests run for a shorter amount of time (continuous sampling) compared to low-torque tests that lasted longer (one 60 s signal record every half hour).

The methodology can be classified into three steps. The first step is the signal acquisition of vibrations originating from the gearbox. The second is signal validation, to check if the signal is as expected. The third step in the procedure is signal processing to find signal signatures that indicate a failure. The signal processing steps are illustrated in Figure 2. Time synchronous averaging (TSA) is a crucial step before autoregression (AR) modelling. It reduces noise in the time signal while enabling isolation of the gear meshing vibration. Furthermore, the Prediction Error (PE) intensity uses a statistical metric known as kurtosis. When the PE consists only of white Gaussian noise, the value of its kurtosis is 3. The value of the kurtosis changes when fault-related information increases in the PE. Thus, one can set a threshold for the kurtosis value.

3. Results and discussion

Test 1a (high torque-low speed) in Figure 3 resulted in a broken tooth on the gear and tooth-root cracks on the pinion tooth; there is a sharp increase in kurtosis values for the gear and a significant rise for the pinion between records 60 and 70. Test 2b (low torque-high speed) in Figure 3 does not have a clear trend in kurtosis values compared to high torque-low speed. However, a trend for the pinion in test 2b can be seen. Wändell [4] made a similar observation and stated that fault-related vibration gets enhanced more than the normal vibration with increasing torque, favouring the higher torque test. He further says that with increasing RPM, normal vibration is enhanced more than fault-related

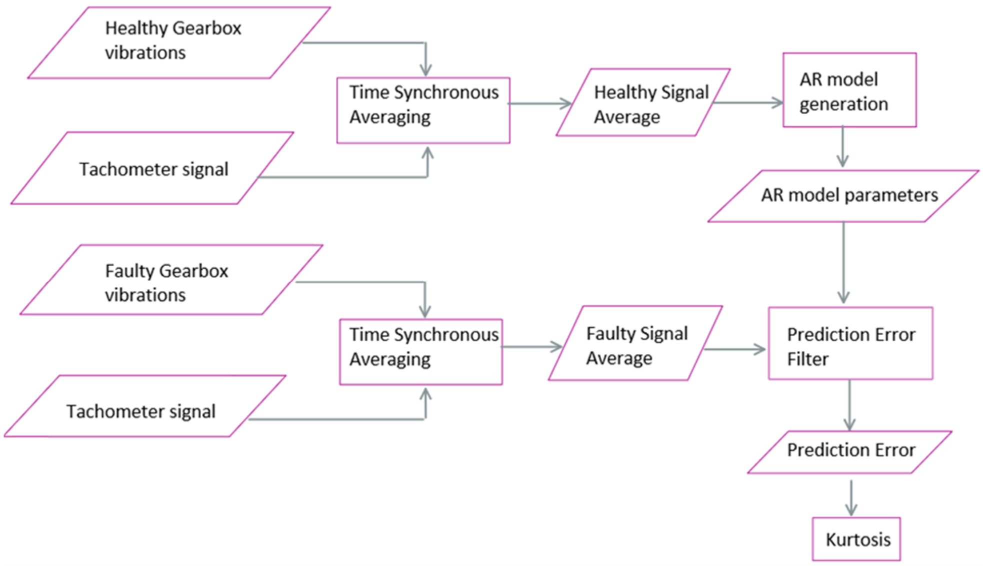

Figure 2. Flowchart illustrating the steps in the signal processing stage. The AR model generates a healthy state TSA signal during the early test cycles. The bottom half of the flowchart represents a similar process of extracting fault-related information from a faulty state signal.

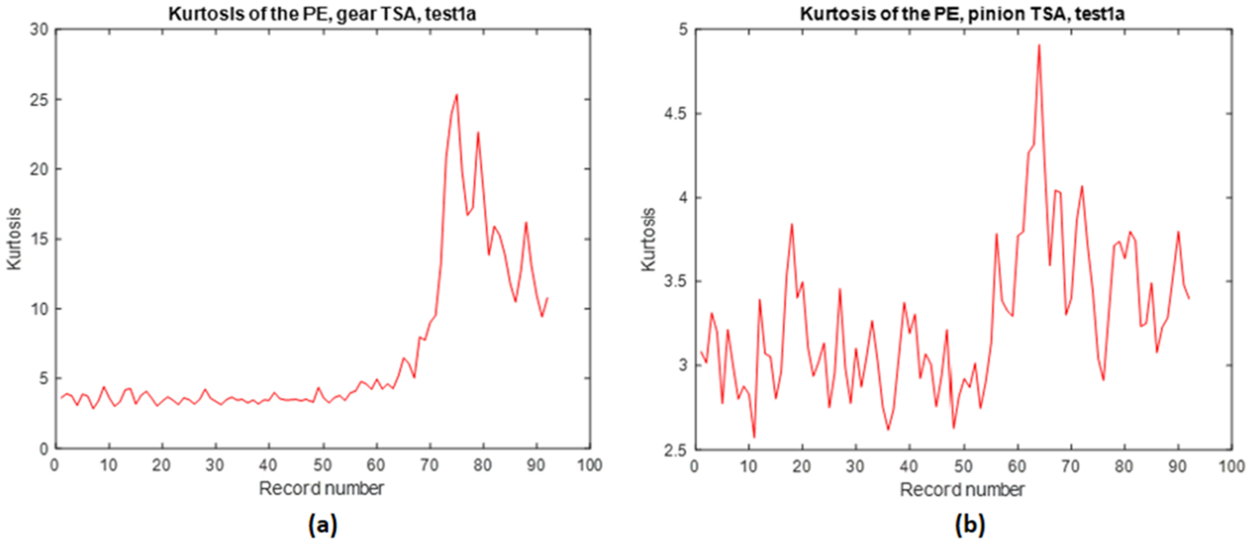

Figure 3. Kurtosis of the PE for test 1a - high-torque (1500 Nm) and low-speed (850 rpm): (a) gear TSA (b) pinion TSA. Gear and pinion both failed in this test.

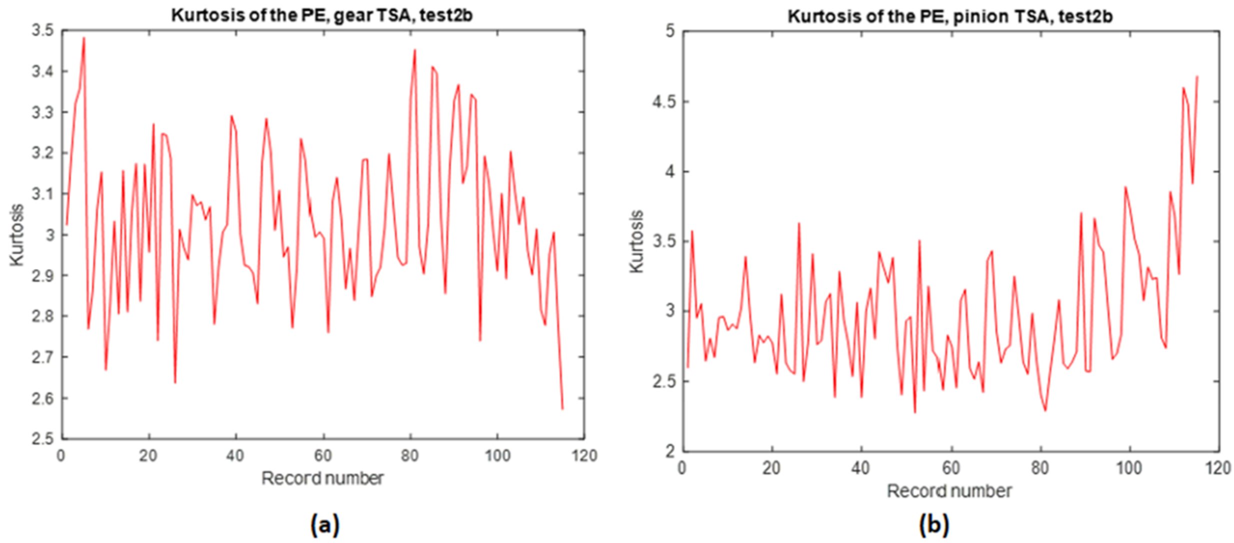

Figure 4. Kurtosis of the PE for test 2b - low-torque (640 Nm) and high-speed (1200 RPM): a) gear TSA b) pinion TSA. Gear survived, and pinion failed in this test.

vibration. Hence, low sensitivity at low torque and high-speed conditions is one of the drawbacks of the proposed methodology. Thus the degree to which failure is detected early is lower at high speed and low torque conditions.

4. Conclusions

The applied methodology in this case study successfully detected failure early in gear fatigue testing. It is automatic, i.e., kurtosis is a statistical metric on which an accurate threshold can be set to initiate a test rig shutdown. Real-time analysis is possible since the AR model generates a healthy state TSA signal during the early test cycles. Subsequent steps can be carried out in real time, as the processes are not computationally intensive. The present methodology's low sensitivity at high-speed and low-torque conditions is a drawback. Further studies can increase the sensitivity under these conditions.

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