Knowing When Enough Is Enough

Predicting Impending Bending Failure in a Test Environment

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Introduction

Detection of impending gear tooth failure is of interest to every entity that utilizes geared transmissions. However, it is of particular significance at the Gear Research Institute (GRI), where sponsored efforts are conducted to establish gear material endurance limits, utilizing gear fatigue tests. Consequently, knowing when a gear is about to fail in each and every test, in a consistent manner, is essential for producing reliable and useful data for the gear industry. To accomplish this end, researchers at GRI and the Drivetrain Technology Center (DTC) at ARL/Penn State have developed a metric called the Average Log Ratio (ALR), described further in the following article. This ALR accurately predicts impending bending failure and is being further developed to predict contact fatigue failures.

The Mission

In all the fatigue testing — the institute's forte — that is conducted at GRI, knowing when a certain, consistent level of failure has occurred is vital. In determining this experimentally, we compare one life-to-failure set of test specimens against the life-to-failure of another set of test specimens in order to compare the durability of one versus the other. A consistent failure criterion is essential in this effort. More discussion and the theoretical basis of this topic are presented here.

The traditional mode of detecting failure in most gear and gear material testing has been to monitor the time domain vibration levels with an accelerometer mounted near the test mesh (Fig. 1). The failure criterion is typically an increase in RMS or peak vibration above a set threshold. This has been found to be very arbitrary, as the level of vibration is dependent on several factors such as the speed, load, tooth geometry, the dynamic response of the test rig system — even background noise.

In recent years, with the wider availability of hardware/software packages that are capable of Fast Fourier Transform (FFT) analysis, GRI has begun to monitor the acceleration levels at specific fundamental frequencies and their harmonics — with significantly improved results. Figure 2 shows a typical frequency spectrum (FFT) for a vibration signal from the 4-square gear test rig in Figure 1. In this spectrum, the fundamental tooth mesh frequency on the torque reversing gear pair is the large peak at about 1,700 Hz. The peaks associated with the fundamental rotational frequency and its harmonics are on the left side of the large tooth mesh peak. The peaks to the right of the tooth mesh peak are further rotational harmonics; harmonics of the tooth mesh frequencies in the test box, harmonics of the tooth mesh frequencies in the torque reversing gear box and their accompanying side-bands. By monitoring energy levels at the specific, relevant frequencies, much more consistent and repeatable results are being obtained, whether it is a running gear bending fatigue test or a surface durability test. While we are still fine-tuning this methodology for surface durability failures, we are confident that we are detecting the initiation of bending fatigue failure of running gear teeth in an extremely consistent and accurate manner — and long before any other technique known can detect this failure.

The basis for monitoring the vibration level at certain fundamental frequencies and its harmonics is that the transmission error vibration excitation from meshing gear pairs contains information pertinent to the health of the gears. Further, in the case of bending fatigue, plastic tooth deformation constitutes the dominant source of gear health changes prior to failure (Ref. 1). This plastic deformation of the teeth leads to deviations of the loaded tooth working surface from a perfect equally spaced position. If the meshing gears are operating at a constant speed and load, the deviations of the loaded tooth-working-surface manifest themselves in the transmission error of the meshing gear pair and in the generated vibration spectra.

In the research at ARL/Penn State, a metric defined as the Average-Log-Ratio (ALR) to quantify the health of the gear has been developed (Ref. 2). The ALR

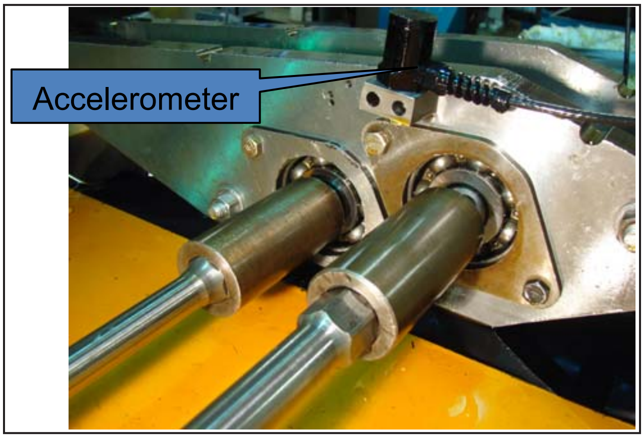

Figure 1 Mounted acceleromator.

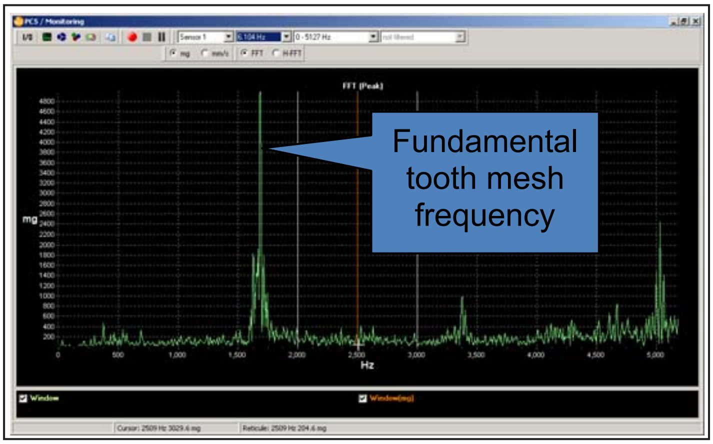

Figure 2 Acceleration spectra.

is defined by the equation below and a value of the ALR significantly larger than zero and increasing in running time is an indication of damage on one or more teeth of the gear.

$$ALR \triangleq \underset{over\ n}{average} \left| \log_e \frac{|\alpha_y(n)|_a}{|\alpha_y(n)|_b} \right| \quad (1)$$

The transducer-response Fourier series coefficients $\alpha_y(n)$ are related to the transmission-error Fourier series coefficients and complex-frequency-response function; more details on Equation 1 are provided in Reference 2; this metric was evaluated for a pair of running spiral bevel gears. Figure 3 shows the progression of the value of the ALR metric for the meshing gears. Increases in the ALR indicate the onset of damage; i.e. — plastic deformation or an increase in transmission error.

In this figure, the value of the ALR, computed with statistical averaging, remained almost constant for approximately 2 hours and 30 minutes running time, but then began to increase monotonically after about 4 hours of operation, when the gear pair loading was reduced. After further running, the ALR metric again increases, as damage to the gear tooth progresses. This methodology could be an effective approach to gear health monitoring in gearboxes as the diagnostics and prognostics of mechanical machinery become an essential requirement of such systems.

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References

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2. Hines, J. A. and W.D. Mark. "Bending Fatigue Damage Detection on Notched Tooth, Spiral Bevel Gear Using the Average-Log-Ratio (ALR) Algorithm," *Mechanical Systems and Signal Processing*, 43, 2014, pp. 44-56.

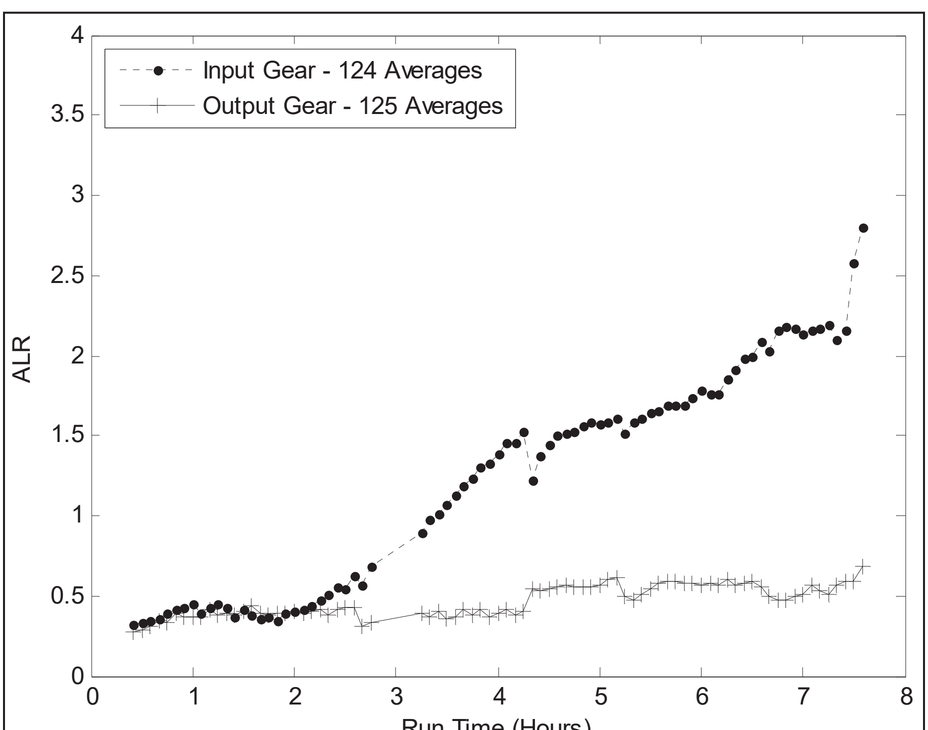

Figure 3 Progression of the value of the ALR metric for the meshing gears.

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