

On-Line Lubricants Health Condition Monitoring in Gearbox Application

John Manyala
Eaton Corp

Massood Atashbar
CEAS Western Michigan University

ABSTRACT

The lubricant wear and degradation is a major cause of failure in industrial machines such as engines, pumps and gearboxes. This is primarily due to contaminants such as metal debris particles and depletion of the chemical and physical properties. This paper presents a low cost, multi-functional sensor for real-time monitoring of both oil level and the debris particles in oil lubricants for a gearbox application. The sensor system achieves a micrometer-order resolution (37.5 μm), high linearity (< 0.5 mm non-linearity) and insensitivity to viscosity changes due to wide temperature fluctuations from -40 °C to 135 °C, and is designed for ease of manufacturing and application in harsh transmission environment. The synergy from simultaneous data analysis from a multi-functional sensor has been demonstrated both qualitatively and quantitatively using mathematical analysis, computer simulation and physical experiments.

INDEX TERMS: Lubricants, Degradation, Wear, Condition monitoring, Hall Effect, Viscosity

CITATION: Manyala, J. and Atashbar, M., "On-Line Lubricants Health Condition Monitoring in Gearbox Application," *SAE Int. J. Fuels Lubr.* 6(3):2013, doi:10.4271/2013-01-9074.

1. INTRODUCTION

The kinematics of gears necessitate sufficient elastohydrodynamic lubrication in order to minimize friction due to sliding and sub-surface shear stresses from tooth loading. The cyclic, high contact, and localized stresses contributes to the lubricant rheology degradation such as high intergranular brittle fracture-parts resulting from hydrogen embrittlement through the lubricant film penetration. The degradation of the oil base stock and additives is a function of the metallic wear particles density, depletion of the chemical and physical properties. During normal machine operation, small wear particles are often generated ranging from 1 to 50 microns in size. When abnormal wear begins, larger particles ranging from 50 to 200 microns are generated. The particle size and distribution is time dependent hence metal wear due to abrasives, fatigue, stress-related and other tribological wear mechanisms needs to be continuously monitored to avert potential catastrophic failures [1].

Studies have shown that there is a strong correlation between debris particle density and progression of gear micro

pitting due to rolling contact fatigue, often leading to gear whine. Extreme gear pitting cases can precipitate into scuffing and even complete tooth fracture [2]. In situ lubricant oil quality monitoring has become an important topic in today's manufacturing and transportation industries in facilitating on-demand maintenance, which improves the economic and ecological efficiency by minimizing machines downtime and maximizing uptime [3]. The dominant technique for oil condition monitoring to date is the periodic off-line oil sampling for laboratory analysis. Typical laboratory analysis includes spectroscopy, ferrography and filtration. Although laboratory analysis procedures are comprehensive and detailed, they are often costly with long lag-times [4]. On-line autonomous lubricant condition based monitoring techniques have been researched. For instance, an acoustic based sensor for detecting debris particles using an emitted signal reflection within the transceiver, also known as the Doppler Effect was developed by [5]. However, this technique is quite sensitive to the transducer positioning since it is susceptible to acoustic emissions from background sources and the signal attenuation varies with the lubricant

temperature. Optical techniques such as scattering counters have been applied in particles detection in lubricants [6]. However, the accuracy of the optical approach suffers from the particulate properties such as refractive index and the presence of air bubbles in lubricants. Other techniques such as capacitive, inductive and vibration-based sensors have also been applied to define the degree of contamination [7-8]. Even though capacitive sensors use relatively simple sensing structures, the measured capacitance reflects not only the presence of particles but also the dielectric properties change such as the acidity and oxidation. Inductive debris sensors are often limited to particle sizes larger than 100 microns, whereas vibration-based techniques are often plagued by the damping characteristics of the lubricants.

Sensors play a key role in feedback control and assessment of systems state, and are expected to operate in dynamic environments in which more than one parameter changes. Advanced sensors for detecting dynamic parameters in harsh gearbox environments must provide not only high signal-to-noise ratio in a wide dynamic range but also possess diagnostic capability. However, the efficacy of a diagnostic scheme is largely dependent on the amount, timely and quality of information available for decision making. Single parameter sensors do not provide sufficient resolving power to reliably determine the extent of lubricants wear and degradation. This paper presents a multi-functional sensor for direct, simultaneous and real-time monitoring of both oil level and the debris particles in oil lubricants based on the 3-D Hall effect sensor in a gearbox application. The compact, rugged and stable monitor system delivers accurate and high fidelity oil level and oil condition monitoring and is ideal for all industrial applications such as power plants, transportation and heavy construction. Lubricant volume monitor ensures sufficient lubricity while the contaminants infiltration monitor provides quasi-continuous evaluation of the health state of gearbox components such as gears, shaft and bearings wear index. Such information is crucial in the determination of safe, reliable and cost effective condition based drain intervals rather than through rigid routine inspections. The novelty of this work is the development of a compact and low cost sensor solution that achieves a micrometer-order resolution ($37.5\text{ }\mu\text{m}$), high linearity (less than 0.5 mm of non-linearity) and insensitivity to viscosity changes due to wide temperature fluctuation from $-40\text{ }^{\circ}\text{C}$ to $135\text{ }^{\circ}\text{C}$.

Abrasive (metallic) wear, ions, broken oil molecules, acids, and oil soaps induce an increase of the oil conductivity. This rises with increasing ion concentration and mobility, hence the electrical conductivity is dependent on the internal oil friction and temperature [9]. The electrical conductivity of most impurities is relatively high as compared to the extremely low conductivity of pure oils. An increase in the electrical conductivity of an electrolyte can be measured by determining the solution's resistance between two electrodes separated by a fixed distance, which correlates to an increase in contaminants within the lubricant. The hydrocarbon aging can also be evident in the additives depletion as reflected by

the reduction in permittivity. The gradient of conductivity or the time derivative of the dielectric constant represents the level of additive depletion while an integral factor of degradation such as the oxidation, acidification, debris content and water content represents the level of contamination. In this paper, contaminant loading of a highly viscous gearbox lubricant and the science of debris detection is discussed. Ferrous debris samples of particle sizes from 1-50 microns collected in the cyclonic gearbox by magnet pick-up are shown in Fig.1.

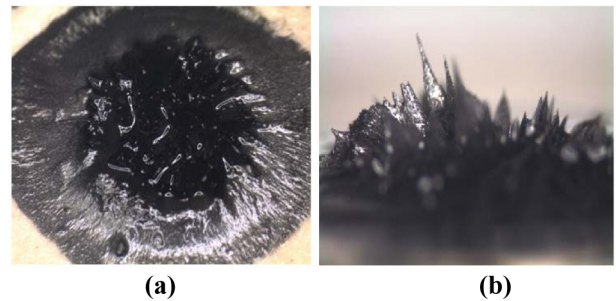


Fig.1. Ferrous debris collected by a magnetic pick-up in a gearbox (a) top view, (b) side view.

2. THEORY

The Hall effect sensor is a magnetic field sensor whose output is an electrical signal that is a function of a mechanical motion. It consists of a permanent magnet, a sensor, and a moving magnetic circuit. The Hall effect was discovered in 1879. The basic description applied to a semiconductor material is illustrated in Fig. 2: A bias current applied across a piece of low doped silicon material (called Hall plate) along the X-axis and a magnetic flux density applied through the plate along the Z-axis results in a voltage along the Y-axis, also known as the Hall voltage V_H . The Hall voltage is directly proportional to the orthogonal component ($B_{\perp}$) of the applied flux density and the bias current (I_{bias}) flowing through the plate [10].

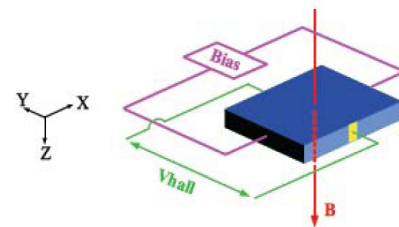


Fig. 2. Hall effect basic principle.

Hall sensors are made using bipolar complementary metal-oxide semiconductor (BICMOS) technology which allows their fabrication directly on the same chip along with microelectronic signal-processing circuitry. Hall effect sensors feature low cost, small size, non-contact and high measurement repeatability. The integrated circuitry allows for

the gain of the system to be adjusted as well as individual calibration for higher degree of accuracy by means of integrated memory cells. Functions such as temperature compensation and signal conditioning can be economically added. Circuit protection and an integrated voltage regulator allows for a wide tolerance to fluctuating supply thresholds [11].

2.1. 3-D Hall Effect Sensor

The 3-D Hall effect technology is based on the conventional planar Hall plates. By adding a structured ferromagnetic layer on the die surface, the resulting construction is sensitive to the magnetic fields parallel to the IC surface. The ferromagnetic layer is called an Integrated Magneto Concentrator (IMC). The process consists of placing the IMC material above the passivation layer and structuring it in conventional photolithographic and etching steps. This process is done during wafer level post-process [12]. The magnetic strength trimming allows for the gain and null adjustments to compensate for mechanical tolerances, which facilitates both static and dynamic oil level sensing. The programmable IC allows calibration of oil viscosity variations with respect to temperature fluctuations empirically through a look-up table.

2.2. Oil Level and Metal Debris Sensing

The multi-functional oil level and metal debris sensor consists of a hollow float with an embedded magnet on the side of the float and the 3-D Hall effect sensor with biasing electronics secured adjacent to the magnet, as shown pictorially in Fig. 3. The hollow float is suspended in oil using adaptable helical spring that is very rigid radially but flexible longitudinally allowing smooth up and down movements relative to buoyancy forces without sticktion and minimal hysteresis. The complete sensor system is located in the sump near the axis of rotation of the lubricant surface which helps alleviate erroneous readings from tilt effect due to varying road grades. The concentric cylinder design acts as an anti-slosh barrier and time synchronous averaging techniques helps compensate for oil sloshing effects. The sensor housing is made of a liquid crystal polymer compound with minimal oil absorption rate that limits potential degradation due to aging.

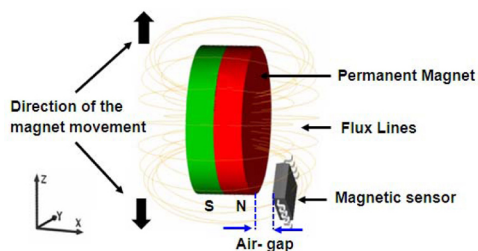


Fig. 3. Encapsulated magnet within a suspended hollow float in oil and the 3-D Hall effect sensor set-up.

The most basic characterization of a magnetic sensor is its transfer curve which defines the relationship between the magnetic field sensed by the device and its corresponding electrical output. As oil enters the bottom of the sensor, the float moves axially within the cylindrical tubing and the change in float position is read by the magnetic sensor. The oil level is determined by triangulating the float position's coordinates from the raw flux signals by computing two orthogonal vector components (B_Y and B_Z) through an arctangent function as follows [13]:

$$\alpha = \text{ATAN}\left(\frac{K_Z \cdot B_Z}{B_Y}\right) \quad (1)$$

where K_Z is a programmable parameter used to compensate the smaller amplitude of B_Z versus B_Y whereas B_Z and B_Y are flux density components. The computed float position is then amplified through a multiplexed chopper amplifier prior to being digitized. The following relationship is employed to determine the corresponding sensor output from the float position:

$$S[\%/deg] = \frac{(\lambda_B - \lambda_A)}{(\alpha_B - \alpha_A)} \quad (2)$$

where λ_B and λ_A represents the sensor's clamped output range while α_B and α_A are the corresponding measured angular positions for a given sampling instant.

The ferrous debris particle content in oil is determined by measuring the ferrous debris build-up on the magnet surface as a function of the orthogonal flux component (B_X) to the IC surface. This represents the magnetic field offsets due to the ferrous debris build-up and the effective change in air-gap. The debris content in terms of output voltage V_{out} is given by the following relationship:

$$V_{out}(B_X[\alpha]) = V_{oq} + \sigma \times B_X[\alpha] \quad (3)$$

where V_{oq} is the programmable quiescent output voltage (i.e. the output voltage when there is zero magnetic field offsets due to debris build-up), σ is the programmable IC sensitivity (in V/G or V/mT). $B_X[\alpha]$ is the applied magnetic flux density orthogonal to the Hall plate surface (in G or mT) provided by the magnetic circuit as a function of the air gap, α . By introducing the thermal effect, equation (3) can be re-written as follows:

$$V_{out}(B_X, T) = V_{oq}(T) + \sigma(T) \times B_X(T) \quad (4)$$

where $V_{out}(B_X, T)$ is thermal coefficient of the programmable quiescent output voltage, $\sigma(T)$ and $B_X(T)$ are thermal