Empirical study on influences of electromagnetic field on Hall Effect sensor for analysing oil lubricant deterioration

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Abstract. This study aims to present the procedure developed for detecting deterioration of oil lubricant under variation of electromagnetic field which was generated by a ferrite-core solenoid coil. The overall diameter of coil was 18.5 mm and the inductance was 22.421 mH from direct current stimulation. The results were then compared to those from frequency stimulation. The optimal efficiency of measurement systems was then assessed by real-time analyzing the metal particle contamination of 3 oil lubricants categorized by grade namely ISO 32, ISO 46 and ISO 68 as well as the viscosity under specific conditions which were flow rate and temperature ranging from 25 °C to 100 °C. The analysis was performed to compare the results from experiments of unused and used (approximately 6 months) oil lubricants. From experiments, the viscosity of oil lubricant was reduced when the temperature exceeded 50 °C. However, the stimulation of coil using 0.9 A direct current could clearly distinguish the difference between the unused and used oil lubricants with metal particle contamination comparing to other values of direct currents applied with 0.42 % of error. Also, the 0.5 kHz of frequency would be the most appropriate value for frequency stimulation with 0.38 % of error.

1. Introduction
Regular monitoring and maintenance of industrial machinery is necessary. Oil lubricant is one of the most important factors for mechanical performance to extend the lifetime of various parts and also increase the efficiency of the machine. Normally, the lifetime of oil lubricant is dependent on the type of oil and the hours of machine operation. However, in practice, oil lubricant could deteriorate sooner. There are many ways to check the properties for oil degeneration analysis such as ultrasonic measurement of viscosity of liquids [1], an IR-absorption sensor system for the determination of engine oil deterioration [2], influencing factors of viscosity measurement by rotational method [3], measurement and correlation of thermophysical properties of waste lubricant oil [4], photoacoustic measurement of liquid viscosity [5], oil contamination monitoring based on dielectric constant measurement [6], the viscosity measurement of oil lubricant based on Archimedes’ principle including Newton’s laws of motion using Hall Effect sensor [7] and application of magnetic field method for measuring lubricant viscosity [8].

This study used a Hall Effect sensor as an instrument measuring voltage variation due to metal particle contamination for analyzing oil lubricant deterioration. The intensity of electromagnetic field generated by coil which was stimulated by direct current and low frequency was also real-time assessed in order to inspect and analyze the properties of oil lubricant during operation effectively.
The results from analysis were then stored in the database for further assessment of machine conditions and maintenance plan.

2. Fundamental method

2.1. Principle of Hall Effect sensor
Galvanomagnetic effect is the phenomenon that electric charges can move in the medium under Lorentz force \( F \) of electromagnetic field on any electric charge \( q \) as illustrated in equation (1) [9]. When magnetic flux \( B \) acting in the direction perpendicular to the conductor sheet with the current flowing through, it can result in the deviation of the charge moving through the conductor that causes the potential different voltage or Hall voltage \( V_H \) between the two poles perpendicular to the direction of the current flow as shown in equation (2). [10]

\[
F = qE + q(v \times B) \quad (1)
\]

\[
V_H = \frac{R_H IB}{d_1} \quad (2)
\]

where \( E \) is the Hall field, \( v \) is the velocity of electron due to electric field, \( R_H \) is the Hall coefficient, \( I \) is the current through each coil and \( d_1 \) is the thickness of Hall Effect sensor.

2.2. Viscosity and fluid dynamic
Viscosity \( \eta \) is an important parameter. It directly relates to the oil lubrication efficiency especially for industrial machinery that can contribute to high machine performance and can operate at full capacity. Equation (3) shows the relation of viscosity and time period when metal particles start moving through the solenoid coil until reaching saturation point under variation of the temperature due machine operation in real time. [11]

\[
\eta = t_{\text{moving}} \frac{F'}{A \rho_f} \quad (3)
\]

where \( t_{\text{moving}} \) is the time period when the particles start moving through the solenoid coil until reaching saturation point (sec), \( \rho_f \) is the density of fluid flow on south direction (km/cm\(^2\)), \( F' \) is the force caused by flow (N) and \( A \) is the area of the pipe where the fluid flows through (cm\(^2\)).

3. Structure of the testing system

3.1. Measurement processing of oil lubricant
The system designed for analysis of oil lubricant deterioration can be divided into 2 parts: 1. the part which can real-time simulate the flow of oil lubricant while the machine is working, consisting of oil pipeline (Ø15 mm), motor pump, flow control valve, flow meter, heater (1.5 kW), PID controller for temperature and thermocouple type K with measurement, and 2. the measuring and processing part including solenoid coil, Hall Effect sensor, signal conditioning and computer for processing and storing data as shown in Figure 1.

3.2. Sensing part and placement of Hall Effect sensor
In this study, the quality of oil was evaluated by creating an electromagnetic field of the solenoid coil at the specified time (ON = 60 sec and OFF = 60 sec) to determine the speed of metal particles accumulating in the cross-section of the ferrite core until reaching the saturation point. The amount of metal particles caused by corrosion and abrasion of industrial machine parts during the operation was directly proportional to the voltage at the output of the Hall Effect sensor. The highest electromagnetic field intensity was at the Hall generator located between the cross-sectional area of the ferrite core and oil pipeline as shown in Figure 2. The output voltage from measurement was then used to analyze the amount of metal particles contaminated in the oil lubricant as well as the viscosity of the oil lubricant.
The results could indicate the quality of the oil lubricant being used and also estimate the service life of the oil lubricant in order to reduce the risk of damage that may occur to industrial machinery.

**Figure 1.** Block diagram of oil lubricant deterioration system.

**Figure 2.** Installation of Hall Effect sensor located between the solenoid coil and the oil pipeline.

### 3.3 Experimental conditions

This study used hydraulic oils No. ISO 32, ISO 46 and ISO 68 as a case study to distinguish between the unused oils and the 6-months-used oils by generating electromagnetic fields using different stimulation methods under specific conditions. The sample of testing oils is as illustrated in Figure 3. The testing oil was placed in the tank with a heater to vary the oil temperature from 25 °C to 100 °C (increasing by the step of 10 °C) similarly to the real machine. Oil was pumped into the 15 mm diameter oil pipeline to measure the flow rate as well as the viscosity. The Hall generator positioned between the solenoid coil and the oil pipeline was used to measure and compare the amount of metal particles contaminating in the unused and used oils.

**Figure 3.** Sample of hydraulic oil No. ISO 32.
4. Electromagnetic field generation

The electromagnetic field generation using the solenoid coil excitation (cylindrical shape, diameter = 9.75 mm, and length = 56 mm), copper wire (SWG 22, 712 turns) with an inductance of 22.421 mH to enhance the Hall Effect sensor performance was calibrated with the measurement of reference metal particles (average diameter = 216 μm) and analyzed 5 times by a scanning electron microscope (SEM). The unused oil without contamination of metal particles were used as the reference voltage \( V_{ref} \) to be compared with the unused oils with metal particles in the amount of 0.2 g, 0.3 g, 0.4 g and 0.5 g, respectively. The relationship between the output voltage of Hall Effect sensor and the amount of metal particles is as shown in Figure 4. From the picture, an ISO 32 oil lubricant was tested at 32 °C with a magnetic field stimulated by a direct current of 0.9 A. From experiment, it was observed that the output voltage of the Hall Effect sensor would increase directly in proportion to the amount of metal particles and rise significantly to the saturation point when the amount of metal particles increased.

![Figure 4](image)

**Figure 4.** The relationship between the output voltage of the Hall Effect sensor and the reference amount of metal particles.

4.1. Experimental results from direct current stimulation

The generation of the electromagnetic field by direct current stimulation was varied from the input current of 0.5 A to 1 A consisting of 0.5 A, 0.6 A, 0.7 A, 0.8 A, 0.9 A, and 1 A (increasing 0.1 A interval) under specific temperature of 50 °C. From experiment, it was found that the electrical current suitable for excitation of the solenoid coil was 0.9 A due to a high concentration of electromagnetic field generated at the cross-section of the ferrite core. Also, this electromagnetic field concentration was adequate for Hall generator to be operated without heat accumulating at the coil comparing to that excited by electric current of 1 A. Figure 5 is a sample test of an ISO 32 hydraulic oil used at operating temperature of 50 °C with an average estimating from 6 times of repeatability. The testing results of a sample of ISO 32 hydraulic oil used under temperature variation from 25 °C to 100 °C when flowing through the heater. Considering the flow rate of oil within the pipeline flowing through Hall Effect sensor, it can be observed that the viscosity of used oils could be reduced similarly to that of the hydraulic oil number ISO 46 and ISO 68 as shown in Figure 6.

![Figure 5](image)

**Figure 5.** Comparison of different direct current stimulations with a sample of ISO 32 hydraulic oil at operating temperature of 50 °C.

4.2. Experimental results from frequency stimulation

The generation of electromagnetic fields using frequency stimulation was to assess the appropriate frequency for experiment by comparing the results of three frequencies: 0.5 kHz, 1 kHz and 1.5 kHz at 30 °C. The optimal frequency for solenoid coil excitation with the highest intensity electromagnetic field generator at the cross-section of the Ferrite core was at low frequency of 0.5 kHz. Comparing to direct current stimulation, it can be noted that frequency excitation results in a higher voltage output from the Hall Effect sensor than that of direct current stimulation. As a result, distinguishing metal
particles contaminated in oil lubricant using frequency excitation can be well performed and contributed to the better accurate results of oil lubricant deterioration analysis. Figure 7 illustrates a sample test of the hydraulic used oil number ISO 32 with an average estimating from 6 times of repeatability. The testing results of ISO 32 hydraulic used oil under temperature variation from 25 °C to 100 °C. Considering the flow rate of oil through the Hall generator placed in The position between the solenoid coil and the pipeline, it can be observed that the viscosity of used oil would be reduced similarly to that of the hydraulic oils No. ISO 46 and ISO 68 that could directly affect the efficiency of the lubricating oil. Details are as shown in Figure 8.

![Figure 6](image1.png)  
**Figure 6.** Test results of ISO 32 hydraulic oil used at temperature ranging from 25 °C to 100 °C with direct current stimulation of 0.9 A.

![Figure 7](image2.png)  
**Figure 7.** Comparison of the results from different frequency excitations of the hydraulic used oil No. ISO 32 at 30 °C.

![Figure 8](image3.png)  
**Figure 8.** Testing results of the hydraulic oil No. ISO 32 used at temperature ranging from 25 °C to 100 °C with frequency stimulation of 0.5 kHz.

### 5. Conclusion and discussion

This study aims to compare the efficiency of the electromagnetic field generated by direct current stimulation and frequency stimulation in order to enhance the optimal efficiency of the Hall generator as the output voltage from the Hall Effect sensor is directly proportional to the amount of magnetic field intensity. Considering the excitation of the coil to create an electromagnetic field, the low frequency stimulation can increase the efficiency of the Hall Effect sensor due to higher Voltage Hall...
by more than 20% without heat accumulation in the solenoid coil compared to the direct current stimulation. The frequency stimulation can also reduce the heat of the solenoid coil by about 48% on average. However, when compared to other types of engine oil, such as fully synthetic SN 0W-20 of a 2,000 cc car with a 9-years lifespan, use of approximately 80,000 km, and engine oil changing period of 10,000 km, it can be observed that the viscosity of fully synthetic engine oil would increase proportionately with the temperature. It is because the engine oil has the ability to wash away soot from combustion caused by the engine's sword that results in increase of the viscosity. For the lubricant used for hydraulic machinery, the viscosity would decrease when the temperature rises due to oxidation reaction. Therefore, the analysis of oil lubricant or engine oil deterioration by considering the viscosity should also consider the type and nature of work of machinery or engine. For instant, the deterioration of the oil used for lubricating machinery without internal combustion systems would result in reduction of the viscosity. On the other hand, the deterioration of the oil used for lubricating engines with internal combustion systems that the oil can lubricate and wash away the soot from the combustion would contribute to increase of the viscosity.

6. References

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