

OFF-LINE CONTAMINANT MONITORING SENSOR ASSESSMENT FOR USED OIL ANALYSIS

S. Raadnui, S. Intasonti

Department of Production and Robotics Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok (KMUTNB), 1518 Pracharaj 1, Bangsue, Bangkok 10800, Thailand

Abstract

It has long been known that the presence of solid contaminants in lubricating oil, whether in a form of wear particles or ingested from the environment are inevitable. The main approach of "before failure" diagnosis or prognosis of the oil-lubricated machinery is to detect lubricant degradation in situ the oil circulating system i.e., additive depletion, physical & chemical oil properties, degradation and solid wear particle generation or dirt ingress. In this particular paper, a solid debris monitoring sensor for used oil monitoring is assessed. The sensor working principal is to measure for the variation of the electrical capacitive responses caused by moisture and solid particles namely dirt and wear particles. The quantitative assessment of this specific sensor is statistically quantified through the utilization of full factorial design of experiments (DOE). The main and interaction effect of moisture, dirt and wear particles on the electrical field response is statistically assessed.

Keywords: contaminant monitoring sensor, full factorial experimental design, lubricant degradation

1. INTRODUCTION

Lubricant is a very important component of prime mover systems; its physical and chemical states are vital to of the whole machines. Used lubricant analysis can be defined as a routine activity for analyzing oil state, oil contamination and machine wear. It is concerned about a lubricated machine component which is operated as a norm. Once an abnormal condition is triggered through the used lubricant analysis, appropriate actions should be taken to correct the root cause or to mitigate a developing failure [1]. Gill oil condition sensor has developed a ferrous particle sensor, which has been utilized in condition monitoring the health of gearbox transmission systems of land-based vehicles, to detect the ferrous wear particles in used lubricating oil [2]. Murali et al. [3] have presented a device for detecting and counting micro metal wear particles in nonconductive lubricating oil inspired by the coulter counting principle, an established technique for counting and sizing debris in an electrolyte solution. In an attempt to distinguish ferrous and non-ferrous metal particles in lubrication oil as well as to eliminate the influences caused by air bubbles and moisture, inductive sensors based on 3-D solenoid coils were designed. The inductance change of the sensor is determined by two variables, namely magnetic permeability and electrical eddy current [4 & 5]. The acoustic detection method uses single or dual ultrasonic transducers to radiate a large amplitude radio frequency pulse and receive the echoes generated by the wear particle in the flow stream. Solid particle size can be obtained based on the echo signal's amplitude; the larger the amplitude, the larger the particle size. The main advantage of the acoustic detection method is that it is capable of detecting and discriminating solid particle from air bubble [6 to 8]. Hamilton et al. [9] created a wear particle image system to detect the wear particle morphological analysis. It consists of a light source, a flow channel, and a high-speed web camera. The light source is used to illuminate the flow channel; the webcam constantly takes images with a high speed as lubricant with wear particle passes the light source. These images are then processed with MATLAB to get individual wear debris characterization, which are critical to identify wear modes. Wu et al. [10] also developed a similar system to extract the characteristics of wear debris particles. Accordingly, lubricant is a vital source of information in the defect avoidance technique, similar to the importance of human blood in disease detection and prevention. Since lubricant is an essential machinery component in any industry, any fault in the lubricant may result in machine downtime and loss of output. Therefore, this causes problems in the industry This paper presents the new alternative technique using capacitive proximity sensor to

measure the contaminant in lubricant. In this particular work, the performance of this specific sensor is assessed systematically through the utilization of statistical design of experiments (DOE). The purpose of this study is to evaluate for the electrical sensor response from the simulated used lubricant of any abnormal conditions such as contaminant ingress, generated wear debris and moisture contaminants.

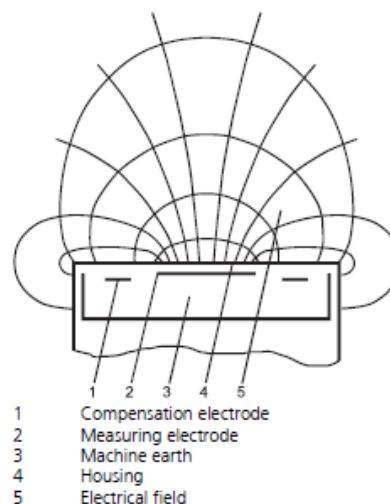
2. MATERIALS AND METHODS

The sensor is a kind of capacitive proximity sensor. The sensor schematic diagram is shown in Figs. 1 & 2, The sensing surface of a capacitive sensor is formed by two concentrically shaped metal electrodes of an unwound capacitor. When an object nears the sensing surface it enters the electrostatic field of the electrodes and changes the capacitance in an oscillator circuit. As a result, the oscillator begins to oscillate. The trigger circuit reads the oscillator's amplitude and when it reaches a specific level the output state of the sensor changes. As the target moves away from the sensor the oscillator's amplitude decreases, switching the sensor output back to its original state. Capacitive sensors depend on the dielectric constant of the target. The larger the dielectric number of a material the easier it detects. The capacitance of the sensor can be expressed as follows:

$$C = \epsilon_0 \epsilon_v A / \delta \quad (1)$$

where ϵ_0 is a dielectric constant of the vacuum, ϵ_v is a dielectric constant of the oil between two poles, A is the available area of poles and δ is the distance between two poles. Because ϵ_v , A , and δ are constant value of the sensor, the capacitance of the sensor is determined by ϵ_v , while the voltage is loaded between the emission pole and the detecting circuit is proportional to the capacitance of the sensor [11].

Figure 1. Schematic diagram of the sensor used in this work.



In this particular work, the LR Device software is used throughout. In this particular circumstance, the value readout from the measuring apparatus is directly related to the input concentration. Contamination in lubricant was measured using the cleanliness level as per National Aerospace Standard 1638 (NAS 1638) by counting the number of particles and dividing the level of contamination into 14 classes ranging from NAS 00 to NAS 12. Each NAS standard step increases the number of particles by a factor of two. Table 1 shows an extrapolation of the contamination concentration and weight of contamination that exceeds level 12 up to NAS 21 [12].

Table 1. Contamination standard as per NAS 1638.

Contamination degree	12	13	14	15	16	17	18	19	20	21
mg/25 ml	1.25	2.50	5.00	10.00	20.00	40.00	80.00	160.00	320.00	640.00
parts per million (ppm)	50	100	200	400	800	1,600	3,200	6,400	12,800	25,600

Measurements of the sensor electrical response value of oil samples have been preliminary assessed which show the variation range of the concentration of NAS 12 of which the weight of contaminants in the oil at 1 gram per 25 milliliters or 40,000 parts per million (ppm), each measurement was a mean value of a repeated record of 20 measurements for each test condition, in relation to the input independent variables such as ferrous particles, brass particles, SiO₂ particles and moisture contamination, as shown in Fig. 3. In addition to the assessment, the design of experiments (DOE) executed of four independent variables, namely: ferrous particles, brass particles, SiO₂ particles and moisture contamination, two levels for each variable.

Figure 2. The off-line contaminant monitoring system used in this work.

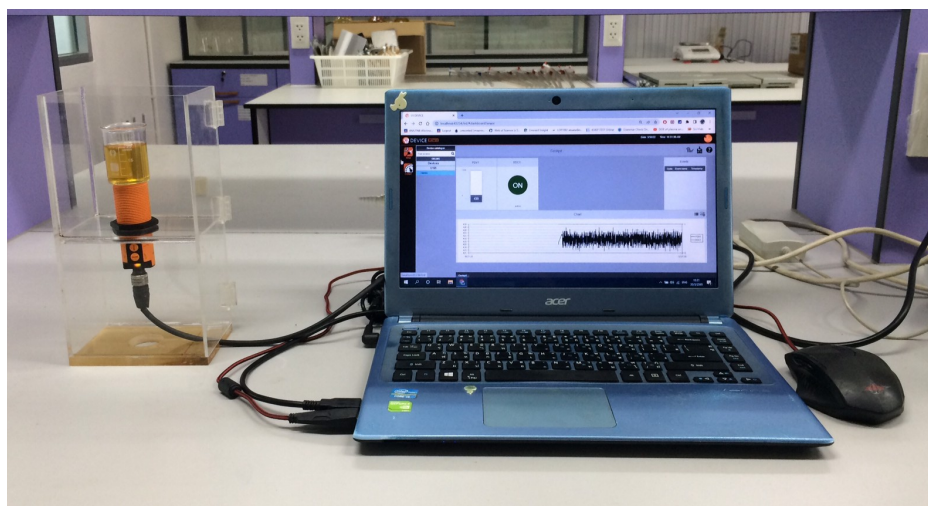
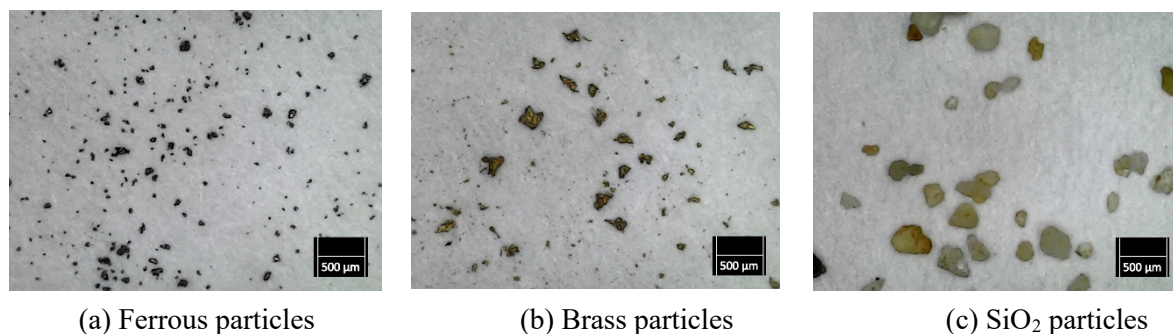


Table 2. Typical values of dependent variables used in this work.

Contaminant	Ferrous	Brass	SiO ₂	Moisture
Specific Gravity	7.9	8.6	2.2	1.0
Hardness (HB)	100	75	820	-
Conductivity (μS/m)	10.1	15.9	-	5.0

Table 2 shows typical properties of ferrous particles, brass particles, SiO₂ particles and water as moisture additions used in this work. Fig. 3 (a), (b) and (c) show typical magnified images of solid particles.

Figure 3. Typical solid particles used in this study.



Details for each independent variables are summarized in Table 3. Utilization of a full factorial design is especially employed for determining important independent variables, which have an effect on the dielectric constant/sensor response value. The efficient of an experiment can be increased by using a statistical design of the experiments which has been utilized as a tool for determining the trivial variables and, thus, determining the sensor performance can be achieved.

Table 3. Detail structure of independent variables for full factorial experimental design.

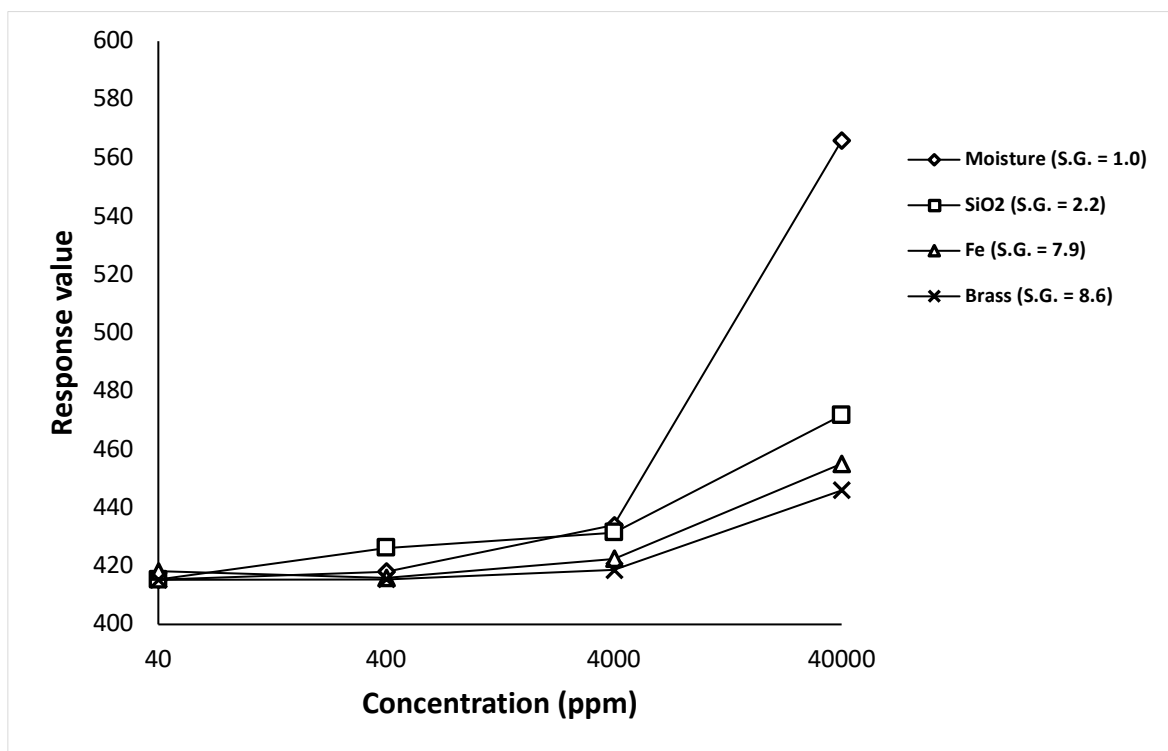
Independent variable	Level 1	Level 2	Remarks
Ferrous particles	None	1 g/25 ml	Particle size range < 300 µm
Brass particles	None	1 g/25 ml	Particle size range < 300 µm
SiO ₂ particles	None	1 g/25 ml	Particle size range < 300 µm
Moisture contamination	None	1 g/25 ml	-

Note: Unused SAE 10W30 engine oil is used throughout the test.

3. RESULTS AND DISCUSSIONS

From the illustration presents in Fig. 4, it can be seen that the variation of the measurement from the sensor can be initially assessed from 0.001 g/25 ml (40 ppm) of contamination upwards, as demonstrated in the plots. In comparison to the NAS 12 contamination standard class range, the monitoring system can be efficiently assessed the contamination level of solid particles and moisture in lubricant based on the specified NAS standard. Response values increased with addition of concentrations and also up to their specific gravity (*S.G.*) as shown in brackets in each specific graph in the plots.

Figure 4. Plot of sensor response value vs concentration of moisture and solid particles.



The most crucial advantages of the utilization of DOE in this particular work of complicated technical systems are, among others, the reduction in experimental expenditure and the determination of unknown phenomena enabling us to conduct systematic subsequent examination. The experiments were carried out using full factorial designs, which varied the level of four main cause variables of the sensor response value. Each contaminant variable was tested at two levels. A total of 16 samples were carried out. A Minitab 17 statistical software was used for the test result analysis.

The plots of main and interaction effects between cause variables are shown in Figs. 5 & 6, respectively. From the main effects plot in Fig. 5, it has been observed that when ferrous particles, brass particles, SiO₂ particles and moisture contamination increases, the sensor response also increases. This may be associated with increasing the level of contaminants in the oil, which causes for the lubricant degradation increases. It has also been noted that the sensitivity of moisture contamination for sensor response value is relatively higher than the other dependent variables.

The interaction effects plot is shown in Fig. 6 for sensor response values. The plots provide the mean response of two factors at all possible combinations of their interactions. If the plotting lines are not parallel, it is an indication of interaction between the two factors [13 & 14]. From the interaction plot in Fig. 6, Interaction between factors ferrous particles vs brass particles, ferrous particles vs SiO₂ particles, ferrous particles vs moisture contamination, brass particles vs SiO₂ particles, brass particles vs moisture contamination and SiO₂ particles vs moisture contamination have a significant effect on the response value.

Figure 5. Main effect plots of individual independent variables.

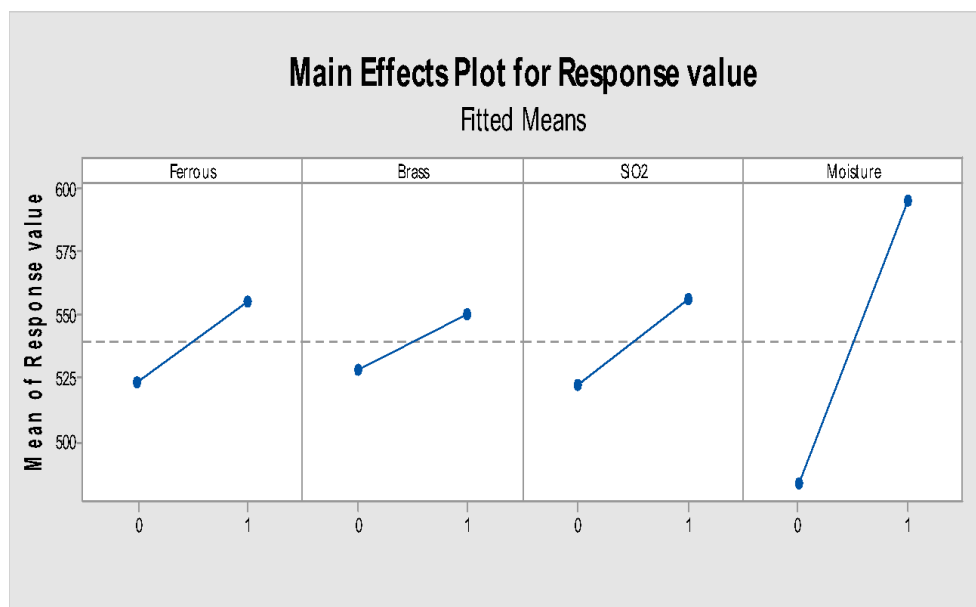
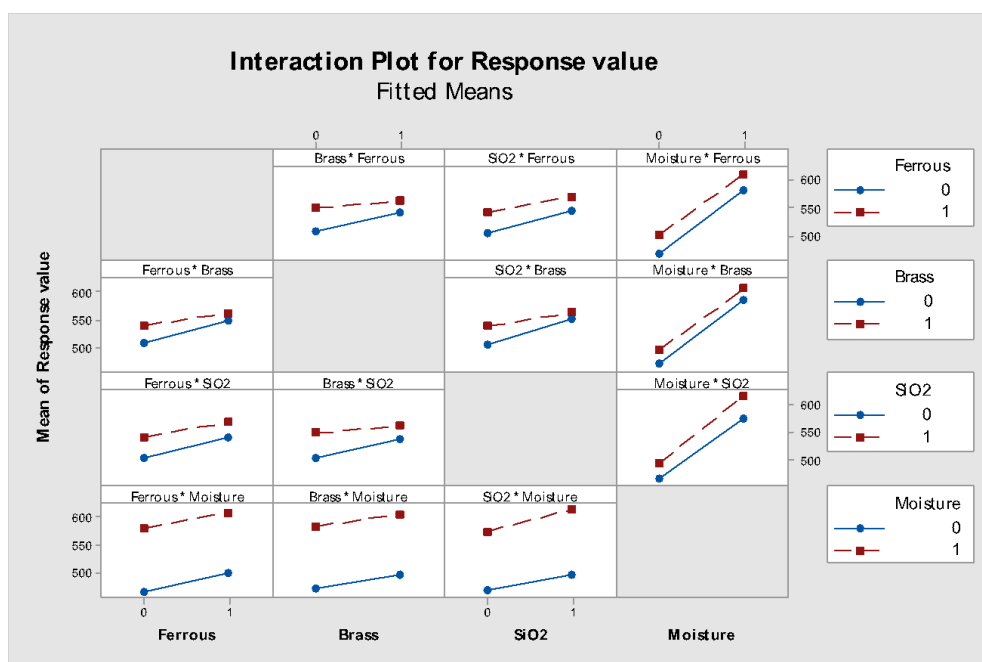


Figure 6. Interaction plots between independent variables.



3. CONCLUSIONS

The following statements can be drawn from this particular work:

1. The sensor in this work distinguishes the relative variation of lubricant quality caused by the simulated contaminants such as ferrous particles, brass particles, SiO₂ particles and moisture contamination with 95% degree of confident.
2. The evaluation of an early failure detection sensor lays the fundamental work for assessing used oil condition systematically. Correlating the oil condition from the sensor output readout for condition monitoring of the oil-lubricated tribological system is encouraging.

3. Future work is needed to evaluate other simulated cause variables, such as other type of metal particles apart from ferrous and brass particles, physical and/or chemical changes. In addition, real world used oil samples from various phases of the oil life cycle from oil lubricated machinery must be tested with the contaminant monitoring sensor before it can be used in real condition monitoring of machinery for industrial applications.

ACKNOWLEDGEMENT

Faculty of Engineering, King Mongkut's University of Technology North Bangkok (KMUTNB), Thailand has supported this work throughout.

REFERENCES

- [1] Oil Analysis Explained. Machinery lubrication. (<https://www.machinerylubrication.com/Read/29598/oil-analysis-report>) [accessed 30.7.20].
- [2] Oil debris sensor. Gill Sensors & Controls. (<https://www.gillsc.com/assets/Uploads/GScondition-CD1599-Iss-5.pdf>) [accessed 30.7.20].
- [3] Murali, S., Xia, X., Jagtiani, A. V., Carletta, J., & Zhe, J. (2009). Capacitive Coulter counting: detection of metal wear particles in lubricant using a microfluidic device. *Smart Materials and Structures*, 18 (3), 037001.
- [4] Du, L., Zhe, J., Carletta, J., Veillette, R., & Choy, F. (2010). Real-time monitoring of wear debris in lubrication oil using a microfluidic inductive Coulter counting device. *Microfluidics and nanofluidics*, 9 (6), pp. 1241-1245.
- [5] Du, L., Zhe, J., Carletta, J. E., & Veillette, R. J. (2010). Inductive Coulter counting: detection and differentiation of metal wear particles in lubricant. *Smart materials and structures*, 19 (5), 057001.
- [6] Nemarich, C. P., Whitesel, H. K., & Sarkady, A. (1988). On-line wear particle monitoring based on ultrasonic detection and discrimination. DAVID TAYLOR RESEARCH CENTER BETHESDA MD PROPULSION AND AUXILIARY SYSTEMS DEPT.
- [7] Xu, C., Zhang, P., Wang, H., Li, Y., & Lv, C. (2015). Ultrasonic echo waveshape features extraction based on QPSO-matching pursuit for online wear debris discrimination. *Mechanical Systems and Signal Processing*, 60, pp. 301-315.
- [8] Du, L., & Zhe, J. (2012). An integrated ultrasonic-inductive pulse sensor for wear debris detection. *Smart materials and structures*, 22 (2), 025003.
- [9] Hamilton, A., Cleary, A., & Quail, F. (2013). Development of a novel wear detection system for wind turbine gearboxes. *IEEE Sensors Journal*, 14 (2), pp. 465-473.
- [10] Wu, T., Wu, H., Du, Y., Kwok, N., & Peng, Z. (2014). Imaged wear debris separation for on-line monitoring using gray level and integrated morphological features. *Wear*, 316 (1-2), pp.19-29.
- [11] Liu, Y., Liu, Z., Xie, Y., & Yao, Z. (2000). Research on an on-line wear condition monitoring system for marine diesel engine. *Tribology International*, 33 (12), pp. 829-835.
- [12] Chaichit, C., Sathamsakul, S., Sriratana, W., & Suesut, T. (2012, March). Hall Effect sensor for measuring metal particles in lubricant. In *International Multi Conference of Engineers and Computer Scientists*, pp. 894-897.
- [13] Montgomery, D. C., & Runger, G. C. (2010). *Applied statistics and probability for engineers*. John Wiley & Sons.
- [14] Montgomery, D. C. (2017). *Design and analysis of experiments*. John Wiley & Sons.