Simulation of a Capacitive Sensor for Wear Metal Analysis of Industrial Oils

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Abstract: Oil analysis is a diagnostic tool used to detect and quantify presence of wear metals and other contaminants in industrial oils. It is a test that helps to determine whether a mechanical system is in a normal or abnormal wear mode. A number of offline techniques for wear metal detection are prevalent. However these are expensive, time consuming, requires skilled labor and do not provide real time data. Accordingly, the goal of this work is to conduct a feasibility study on the application of capacitive sensing principle for detecting abnormal wear conditions in industrial lubes. The detection is based on sensing the change in relative permittivity of oil as the wear metals pass through the capacitor electrodes. Three configurations, namely, parallel plate, interdigitated and meandering capacitor electrodes have been studied. Simulation results, corroborated by experimental results suggest that the capacitance change is directly proportional to the wear particle concentration.

Keywords: Wear particle, Interdigitated (IDT).

1. Introduction

Lubricant oil is a key component used in industries in order to ensure proper functioning of industrial machinery such as turbines, gears, bearings and compressors. The condition of the oil deteriorates over time due to machine operation, and needs to be monitored frequently so as to prevent structural damage to the machinery. Oil analysis is a diagnostic tool used to detect and quantify presence of wear metals and other contaminants in the lubricant of oil wetted systems. Just as a blood sample analysis reveals details of the physiological well-being of an individual, the analysis of a lubricant sample provides important information on the health of the machine. It is a test that helps to determine whether a mechanical system is in a normal or abnormal wear mode.

The presence of large metal particles (typically, greater than 10 microns) indicates an abnormal wear mode, whereas the presence of fine particles is more indicative of the normal wear condition of the machine. Figure 1 indicates the contributions of the large and fine metal particles as a function of time.

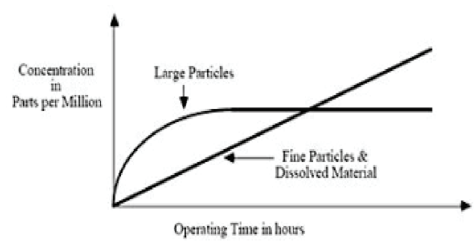

Figure 1: Influence of particle size on oil ageing [1].

Just as a blood sample analysis reveals details of the physiological well-being of a human being, the analysis of a lubricant sample provides important information on the health of the machine. It is a test that helps to determine whether a mechanical system is in a normal or abnormal wear mode.

The aim of this work is to conduct a feasibility study on application of capacitive sensing principle for detecting abnormal wear conditions in industrial lubes. The paper is organized as follows. Firstly, the literature review and motivation for this work is presented. Next, a detailed account of the numerical modeling is presented. Finally, the simulation and experimental results are presented and key conclusions are drawn.

2. Background and Motivation

This section summarizes the various wear metal analysis techniques reported in literature. A capacitive sensor for measuring wear metal particles with sizes exceeding 1000 microns is reported in [2]. Any contamination due to metallic impurities changes the dielectric constant in between the two plates of the grid capacitor leading to change in capacitance. This change in capacitance is measured by the impedance analyzer. Likewise a capacitive sensor based portable oil analyzer is presented in [3]. This work reports the dependence of dielectric constant of contaminated oil on the frequency of interrogation. Impedance spectroscopy indicates that water contamination dominates dielectric constant at lower frequencies of 100-500 Hz, while metal particle contamination dominates at 120 kHz and higher frequencies. A parallel plate MEMS capacitor based on Coulter counting principle for wear particle analysis is presented in [4]. These sensors are capable of detecting fine wear particles in sub- micron range.

Elemental analysis of wear metal contamination can also be measured by atomic absorption spectroscopy (AAS), atomic/optical emission spectroscopy (AES/OES), mass spectrometry (MS), X-ray fluorescence spectroscopy (XRF), ferrography and magnetic chip detectors [5]. Spectroscopic methods usually require pre-treatment of oil samples before analysis. In atomic spectroscopic methods the excitation source, atomizes and often also ionizes the elements of the sample. In the AAS method, a light source with the characteristic wavelength of the determined metal is emitted from a hollow cathode lamp and is absorbed by the metal atoms. The degree of absorption is then detected to determine the presence and concentration of a particular metal [5]. In OES techniques the metal atoms and/or ions are excited with the thermal energy of the excitation source. When the excitation state dies, an element-specific emission spectrum is produced. With the selection and isolation of a certain emission line, the concentration of the metal can be determined. In the XRF instrument each atom emits radiation in the X-ray region after stimulation. The detection system can measure the amount of metal atoms in the sample by determining the amount of X-ray energy produced by the atoms at their characteristic wavelengths [5]. The XRF technique has been used successfully to determine additive metals and wear metals in oil samples, as well as wear metals in lubricant filters. All the above mentioned techniques require extensive pre-treatment of the sample, necessitating the need for skilled labor. Also these instruments are bulky and not suited for portable on-site and real-time applications.

Optical emission spectroscopy for oil analysis has been reported in [6] and [7]. The scattering measurements are used for determination of wear particles, whereas the optical UV-VIS-IR spectroscopy is used for finding water content in the oil and fluorescence spectroscopy is used for viscosity determination. Another configuration of optical emission spectroscopy uses microfluidic channels etched on glass substrate as presented in [7]. Simultaneous determination of water contamination and wear particle contamination is carried out using the scattered and fluorescence spectral data. These optical systems are light weight and do not need extensive preparation time. However, these optical techniques cannot be applied on-line for real time measurements.

Thus the requirement is to develop a simple, easy to use, cost-effective, real-time sensor that does not need extensive sample preparation and can be easily integrated with a Programmable Logic Controller (PLC) to obtain real time data for automated analysis.

Accordingly, the goal of this work is to conduct a feasibility study on application of capacitive sensing principle for detecting abnormal wear conditions in industrial lubes.

3. Methods

This section provides a detailed account of the numerical modeling of three configurations of the capacitive sensor, namely, parallel plate, interdigitated (IDT) and meandering electrodes. The sensing principle, underlying assumptions and step-by-step model set-up procedure are outlined.

3.1. Sensing principle and assumptions:

The sensing principle is based on detecting change in capacitance between two plates of a capacitor due to the presence of wear metal contaminants in oil. Polarity of oil changes due to presence of conducting metal debris inside it, which in turn leads to change in dielectric constant of oil and can be detected using the capacitive sensors.

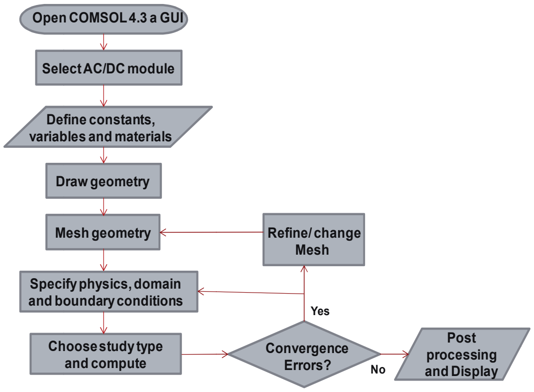

Figure 2: Simulation flow of wear metal sensor model.

Three configurations of capacitor electrodes, namely, parallel plate, interdigitated and meandering electrodes have been studied using COMSOL 4.3a. The electrostatics formulation in AC/DC module of COMSOL was used to evaluate the sensitivity, defined as change in capacitance per a fixed number of particles. The model assumes that the wear particles are spherical in nature, the capacitors are completely immersed in oil medium, and that the fluid is in steady state. Further it is assumed that no other source of contamination is present, so the change in capacitance is purely due to wear particles only.

3.2. Simulation set-up:

The step-by-step set-up procedure followed for the sensor model simulation in COMSOL is highlighted in Figure 2. Following are the details.

Physics:
The electrostatics formulation in the AC/DC module solves the Poisson's equation to calculate the potential distribution across the field space.

$$-\nabla.(\varepsilon_0 \varepsilon_r \nabla V) = \rho$$

Where,
ε_0 is the permittivity of free space, ε_r is the relative permittivity, and ρ is the space charge density.
The electric field is obtained from the gradient of V.

$$E = -\nabla V\ .$$

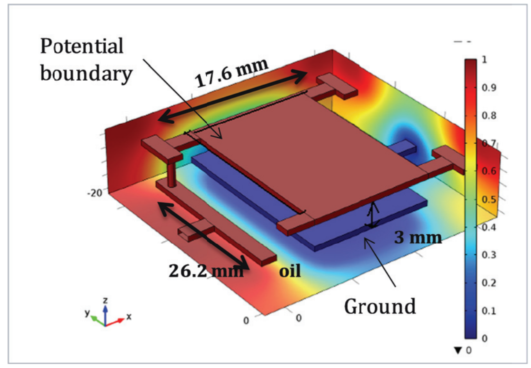

Figure 3: Model of parallel plate capacitor.

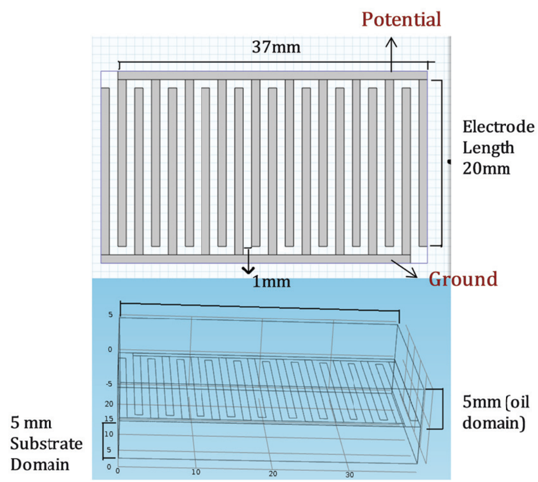

Figure 4: Model of Interdigitated capacitor.

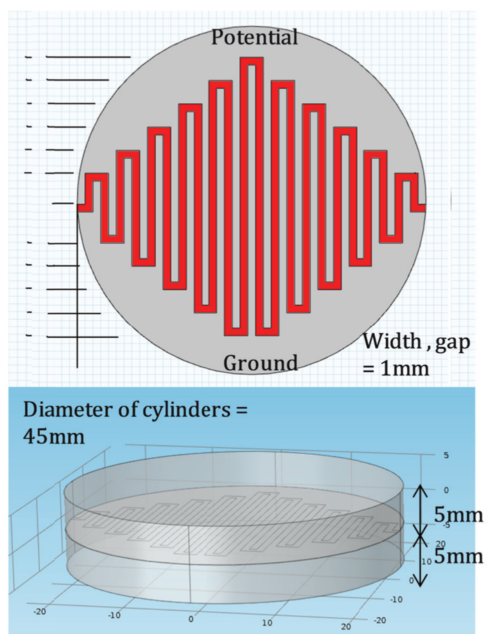

Figure 5: Model of meandering capacitor.

Geometry:
A 3D model was built using the COMSOL GUI. The parallel plate capacitor model is based on a well-known example from COMSOL Model Library. Dimensions of the capacitor were modified to detect wear particles in the diameter range of 100-1000 microns. The model is shown in Figure 3. However, using this capacitor in the field or tank would introduce disturbance in the flow of the oil. To reduce the impact on the fluid flow, a planar structure of sensor was considered. In planar structures, the electrodes are etched on a substrate. The thickness or height of electrode is very small (1000 times) when compared to the height of the substrate. Hence, the height is neglected and the electrode has been modeled as a 2D structure. The geometries of IDT capacitor and meandering capacitor are shown in Figures 5 and 6 respectively. The particles were modeled as spheres with diameters ranging from 100 to 600 µm.

Boundary conditions:
One of the two electrodes of the capacitor was modeled using the *Potential* boundary condition. The other electrode was modeled as a *Ground.*
A potential difference of 1V was applied between the two electrodes. The boundary conditions are depicted in Figures 3, 4 and 5.

Materials:
The electrodes were assumed to be made up of copper. The substrate material is chosen to be FR4 with a dielectric constant of 4.5. The top half of the domain is considered to be filled with oil with dielectric constant of 2.3.

Meshing and study settings:
Fine mesh was chosen for all the cases. Stationary and parametric analyses were performed. The base-line simulations were performed to calculate the absolute capacitance in case absence of particles. This was taken as the reference value for computing change in capacitance with the increasing number of particles. The impact of particle size and the number of particles were then studied by performing a parametric analysis. Lastly, to compare the sensitivities of the three configurations, a uniform distribution of 12 particles is considered as shown in the Figure 6. All the remaining parameters are kept identical. Hence the only change in the result would be due to the change in electrode configuration itself.

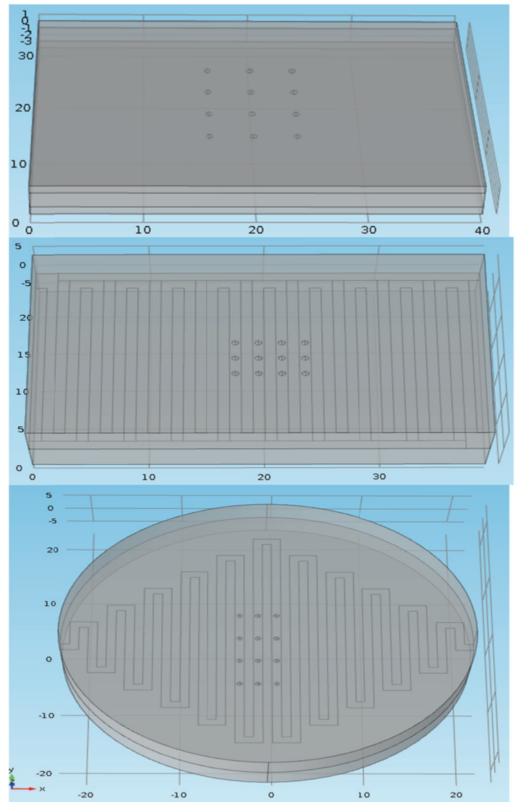

Figure 6: Simulation set-up for sensitivity performance comparison.

6. Results and discussion:

6.1. Simulation results:

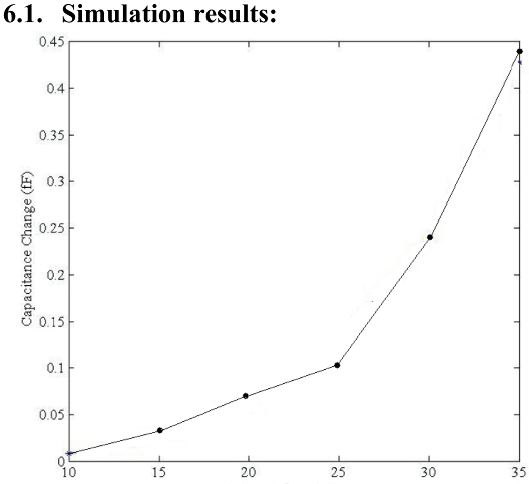

Figure 7: Change in capacitance with particle diameter.

To have higher confidence in the results, the simulation model had to be validated. To establish the validity of the capacitor model, the simulation results were compared against results published in literature. A model of the IDT sensor proposed for sugar concentration sensing reported in [8], was created in COMSOL. The simulation yielded a capacitance of 8.16 pF which closely matches with the value of 8.02 pF published in the paper.
The change in capacitance as a function of the particle size for parallel plate configuration is shown in Figure 7. Thus, the change in capacitance increases with increase in particle diameter. This is valid for all the three configurations.

Table 1: Change in capacitance with number of particles.

No of particles	Capacitance change (pf) for IDT capacitor	Capacitance change (pf) for meandering capacitor
	Ref = 10.66 pf	Ref = 12.75 pf
3	0.05 pf	0.10 pf
6	0 .11 pf	0.18 pf
9	0.16 pf	0.25 pf
12	0.20 pf	0.30 pf

Table 1 shows the performance of the planar sensors with increasing number of particles. One can see that the change in capacitance is of the order of 0.05 pf per 3 particles for the IDT and of the order of 0.07 pf per 3 particles for the meandering capacitors. Thus the change in capacitance is directly indicative of the wear particle concentration.
Table 2 lists the comparison between three sensor configurations. For 12 wear particles, uniformly distributed; the change in capacitance is around 95fF for the parallel plate capacitor, 200fF for an IDT capacitor and 300fF for a meandering capacitor. Thus, the meandering capacitor configuration is the most sensitive (factor of 3 times that of parallel plate) to wear metal detection.

Table 2: Performance comparison of parallel plate, IDT and meandering sensors.

Parameter	Parallel plate sensor	Inter-digitated sensor	Meander-ing sensor
Reference capacitance	24.44 pf	10.56 pf	12.75 pf
Change in capacitance with 9 particles	0.07 pf	0.16 pf	0.25 pf
Change in capacitance with 12 particles	0.09 pf	0.20 pf	0.30 pf

6.2. Experimental results:

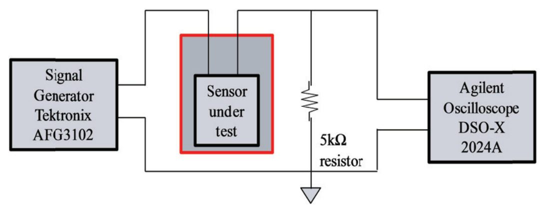

Figure 8: Block diagram of experimental set-up for sensor characterization.

The sensors designed using COMSOL are fabricated on FR4 substrate. The sensor capacitor is placed in a vial containing 100ml of machine oil. A first order RC filter is realized by connecting the capacitive sensor in series as shown in Figure 8. The output is monitored across the 5kΩ resistor. The input signal frequency is swept from 100 kHz to 50 MHz at 5Vp-p amplitude. The corresponding output is monitored on the oscilloscope.
From simulation, the expected value of cut-off frequency is 3.01 MHz. The cut-off frequency is the frequency at which the amplitude of the filter output is about half of its maximum amplitude. This is in close agreement with the experimental value of 4 MHz (± 1MHz). This is the average value of measurements performed in air for two such sets of sensors. The maximum occurs at a frequency of around 30 MHz. Further testing of the IDT sensor with fine metal dust contaminant revealed that the output of the sensor changes as much as 100mVpp for every 1g of metallic contamination. This is in agreement with the simulation results which pointed out to the fact

that the capacitance change is indicative of the concentration of wear particles.

7. Conclusions

The principle of capacitive sensing for wear particle detection of industrial oils has been explored in this work. To understand the behavior of these sensors with increasing wear particle concentration and wear particle size, a numerical model was built using COMSOL Multiphysics. Simulation studies revealed that the change in capacitance is proportional to the change in particle size as well as the particle concentration. The models were validated by comparing with published literature. Experimental characterization of the IDT and meandering sensors further indicated that the simulated and experimental values of cut-off frequencies (~ 3MHz) are in agreement with each other. The output of the IDT sensor changed by a factor of 100 mVpp for 1g increase in metallic contamination in 100 ml volume of oil. Thus COMSOL has been successfully used to model and understand the behavior of capacitive sensors for wear metal detection in industrial oils. Future work will focus on optimization of sensor design for improved sensitivity performance.

7. References

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