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Safal Kshetri
*Iowa State University*, skshetri@iastate.edu

Brian L. Steward
*Iowa State University*, bsteward@iastate.edu

Stuart J. Birrell
*Iowa State University*, sbirrell@iastate.edu

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Dielectric Spectroscopic Sensor for Particle Contaminant Detection in Hydraulic Fluids

Safal Kshetri; Brian L. Steward; Stuart J. Birrell
Iowa State University,
Agricultural and Biosystems Engineering Department
1340 Elings Hall, Ames, IA 50011

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Abstract.
Particulate contamination of hydraulic fluids is one of the major causes of mechanical wear of hydraulic components resulting in system inefficiency and failure. Potential failures of hydraulic systems could be avoided through continuously monitoring the condition of the fluid. A practical contaminant sensor was developed to estimate the level of particulate contamination in hydraulic fluids. The sensor was designed to be installed on vehicle and provide in-line measurements of contaminated hydraulic fluid. The sensor used dielectric spectroscopy for measuring contaminants. To investigate the performance of the dielectric sensor two tests were performed with different diameter central rods using iron particles as hydraulic contaminants. A hydraulic test circuit was built and a methodology was developed for the tests. An eight-channel particle counter was used for calibration of the dielectric sensor. PLS models were developed to investigate the relationship between dielectric spectra and iron particle counts. The RMSEC and RMSECV for the sensor with a central rod diameter of 6.35 mm were 1.1 ISO 4406 scale numbers and 1.39 scale numbers respectively. For a 17.7 mm diameter rod, the respective values were 0.62 and 0.77. The sensor shows good potential estimate of the cleanliness level of hydraulic fluid mixed with iron contaminants.

Keywords. dielectric sensor, dielectric spectroscopy, ISO 4406 cleanliness code, hydraulic contaminants

Introduction
Advances in fluid power system technology have led to the development of sophisticated high-pressure systems. These systems need high quality and clean fluid for reliable and efficient operation. About 70 percent
of all hydraulic system failures are due to contaminants in the fluid (Singh, Lathkar, & Basu, 2012). Even if the failures do not occur immediately, the high levels of contamination can sharply reduce efficiency of the hydraulic systems. Increasing contamination levels and changes in the fluid properties could be clues of possible failures of hydraulic components. A sensor capable of continuously monitoring the condition of the fluid during equipment operation could have significant impact by preventing machinery failure with associated losses.

Hydraulic fluid condition can be determined by measuring viscosity, refractive index, density, base number (BN), acid number (AN), water content, metals (additive and wear metals), color and flash point. Changes in fluid dielectric properties are another indication of changes in the quality of the working fluid (Carey & Hayzen, 2001). The oxidation and depletion of additives will affect fluid chemistry. Additionally, the presence of contaminants such as water, soot particles, acid combustion particles, glycols, ferrous and non-ferrous metallic particles could also lead to changes in dielectric properties (Perez & Hadfield, 2011).

Particle counting is the most common methods used for detection of contaminants in a hydraulic fluid. Commercially available automatic particle counters sense light blockage by particles and use code ISO 4406:1999 to report the quantity of solid particles in the fluid. The ISO code 4406:1999 provides a way to simplify the reporting of particle count data by converting the numbers of particles into broad classes or codes based on sizes. The reported code is expressed in a 3 scale number format; for example, 22/18/13, where the first, second and third scale numbers separated by forward slashes represent the number of particles equal to or larger than 4µm, 6 µm, and 14 µm, respectively, in one milliliter of fluid (ISO 4406:1999).

The dielectric properties of a material explain the electrical interaction between the material and an electric field. Normally, this interaction depends on the frequency of the applied field and can be described best using relative complex permittivity, \( \varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \), where the real part \( \varepsilon_r' \) denotes the dielectric constant of the material and the imaginary part \( \varepsilon_r'' \) denotes the dielectric loss factor. The dielectric constant is a measure of the ability of the material to store electrical energy; while the loss factor is a measure of energy loss in a material relative to the applied external electrical field. The relative complex permittivity can be measured as a function of frequency using dielectric spectroscopy (Von Hippel, 1954a). Dielectric spectroscopy has been used for comparing different petroleum fractions (Folgero, 1998; Tjomsland, et al., 1996), sensing moisture dynamics in oil impregnated pressboard (Sheiretov & Zahn, 1995), and monitoring of moisture content and insulation degradation in oil transformers (Koch & Feser, 2004).

The objective of this research was to investigate the ability of a sensor to determine iron particle contaminants using dielectric measurements of hydraulic fluid passing through the sensors. The sensor was also designed to be low cost for off-road vehicle installation and to provide in-line measurements of contaminants during operation.

Materials and methods

Dielectric properties of the hydraulic test fluid samples were measured using an HP 4192 LF Impedance Analyzer (Hewlett-Packard, Palo Alto, CA, USA) connected to the dielectric sensor developed in the research project. The dielectric properties, through measured conductance and susceptance, of the samples were measured over frequencies ranging from 5 Hz to 13 MHz. An experimental hydraulic apparatus was developed for testing performance of the dielectric sensor. Finally, the partial least squares (PLS) regression method was used for analysis of the experimentally collected data.

Dielectric Sensor Design

The dielectric sensor designed and fabricated for testing consisted of three parts: the housing, the sensing unit, and the hydraulic adapter. The housing (Figure 1) was built to primarily enclose and support the sensing unit, and to provide connections for the hydraulic adapters. The split design of the housing was necessary for simplifying electrical connections to the sensing unit. The dimensions of the tubular passage and threaded ports of the housing were chosen to provide flexibility in accommodating any future modifications of sensing unit and hydraulic adapters. The housing also has an electrical connector for receiving electrical ground potential during the measurement.
The sensing unit was machined to fit into the tubular passage formed by the two halves of the housing. The unit was built by assembling a number of metallic and dielectric parts that were fabricated to allow passage of fluid through the sensor (Figure 2). This design enabled the sensor to be connected in-line with a hydraulic circuit. The metallic parts of the sensing unit are the outer conductor, central rod, guard rings, shield, and rod holders (Figure 3). The main sensing section of the unit was designed as a cylindrical capacitor in which outer conductor and central rod form the two main electrodes of the capacitive sensing unit. The outer conductor receives the excited sinusoidal electrical signal through a coaxial cable, while the central rod lying inner and coaxial to the outer conductor could be electrically grounded through metallic rod holders that make physical contact with the housing. The rod holders with kidney shaped openings were machined to hold the central conductor in its position. Any medium between the two coaxial electrodes acts as dielectric and has direct influence on the capacitance of the sensor.
Figure 3. Cutaway view of the sensor housing shows the housing as well as the coaxial sensing unit with different metallic and dielectric parts.

The diameter of the outer conductor was chosen to match with that of hydraulic connector to maintain laminar flow of fluid. For the testing purposes, a dash 16 SAE O-Ring Boss hydraulic connection was selected to ease manufacturability and minimize pressure drop. The central rod was designed with gradually decreasing diameter at the sides and tapered ends to maintain steady fluid flow through the sensing unit.

On either side of the outer conductor, two metallic guard rings were placed coaxially and separated from the outer conductor by thin dielectric rings. These rings were used to minimize fringe effects from the edges of the outer conductor, and thus, focus the electric field on the hydraulic fluid in the sensing volume. The outer conductor and guard rings were surrounded by a tubular metallic layer called a shield. It also received an electrical signal through a coaxial cable. The shield and guard rings were connected to each other by two small metallic springs, which ensured electrical conduction was maintained between these two parts. The shield and guards were driven independently of the outer conductor so that sensing area was isolated from any potential external disturbances such as electrical noise.

The dielectric parts in the sensing unit were used as electrical insulators and physical spacers. These components were fabricated from fluorinated ethylene-propylene (FEP). FEP was chosen as a dielectric material for its stable dielectric constant and low loss factor over a wide range of high frequencies, and compatibility with oil. Hydraulic adapters were machined to fit into the threaded portion of the housing. These adapters had -16 SAE O Ring Boss female ports for connection to a hydraulic circuit.

Hydraulic test circuits

The hydraulic circuits developed to test the dielectric sensor consisted of a fluid cleaning circuit and a test circuit (Figure 4). The hydraulic fluid in the oil drum may not be sufficiently clean. Therefore, the fluid cleaning circuit was used to clean the hydraulic fluid before it was introduced into the test circuit. The fluid cleaning circuit consisted of filters through which the hydraulic fluid was circulated several times and then transferred to the test circuit. The test circuit consisted of two reservoirs. One of them stored contaminated fluid prepared in the laboratory by mixing a high dose of iron particulates with the clean fluid, while the other was used to store samples of fluid used for testing. Peristaltic pumps were used to move the fluid in the circuit to minimize internal wear of particles. A filter was added in the test circuit to ensure the test fluid achieved the desired ISO cleanliness level required at the beginning of the experiment. The fluid passed through a coil in a constant temperature bath to maintain steady fluid temperature throughout the experiment. To calibrate the dielectric sensor, an in-line, light-blockage particle counter was added in the test circuit. Shut off valves and check valves were used to achieve desired flow operation required during the experiment.
Test procedure

Two tests were performed using the central rods of different diameters. The first test was performed using the rod diameter of 6.35 mm. This diameter was initially considered in the research for impedance matching of the dielectric sensor with electrical source to maximize electrical power transfer. However, after realizing that this rod size led to a small sensing capacitance relative to stray capacitance, a second test was performed with a larger rod diameter of 17.7 mm to determine if it would improve the sensing performance.

Spherical iron powder less than 10 micrometer in diameter was used as particulate contaminants for the test. The hydraulic fluid used during the test was Shell Tellus ISO VG 46 hydraulic oil. Prior to the experiment the hydraulic fluid was cleaned in the fluid cleaning circuit. About 1000 ml of this clean fluid was drawn out into a reservoir and mixed with iron particulates to produce a highly concentrated contaminant fluid mixture. In a separate reservoir about 2000 ml of clean hydraulic fluid was stored as the test fluid. These fluids were continuously stirred using magnetic stirrers to minimize settling of the particulate contaminants. The temperature controlled hot bath was set to maintain the fluid temperature at fixed temperature throughout the test. Electrical terminals from the dielectric sensor were connected to HP 4192A LF impedance analyzer.

The test fluid was circulated through the test circuit, and the ISO cleanliness level was monitored using the particle counter. Filtration was used to bring the ISO cleanliness level to the desired base level. The experiment was started after temperature and cleanliness level reached a steady state. Clean fluid at the base level was the first sample measured using the impedance analyzer. A small amount of the contaminant mixture fluid was then injected to the test fluid in a controlled manner to produce a sample test fluid with the ISO cleanliness code level slightly higher than before. After the ISO cleanliness level became steady, this new sample test fluid was measured. This process of injecting contaminants and taking measurements was continued until the test fluid reached the highest level of contamination that the particle counter could effectively measure. This experiment was replicated three times. To make the replications independent, after completion of each replication, the test circuit was flushed out with clean fluid and a new volume of test fluid was used for next replication.

To get reading from the dielectric sensor, the impedance analyzer was programmed to measure both conductance and susceptance at 63 frequencies ranging from 5 Hz to 13 MHz sampled linearly within decades. This dielectric spectroscopy was performed three times for each sample. At the same time, particle count measurements were acquired over 60 second time intervals, usually resulting in acquisition of nine particle count samples while the dielectric measurement were being acquired.

Data Analysis

After the completion of the tests, partial least squares regression (PLS regression) analysis was performed to develop models relating spectral measurements to particle counts. The counts obtained from the particle counter for different particle sizes based on ISO 4406 could not be directly correlated with the spectral data.
Since the dielectric sensor was measuring bulk dielectric properties of the fluid, it was assumed that individual larger particles would have greater influence on dielectric response of the sensor because of their ability to displace a larger fluid volume than the smaller particles in the fluid. Therefore, a weighted composite cleanliness code was developed using the data from particle counter, and regressed onto the dielectric spectral data. Cross validation was performed to assess the predictive ability of the models. Root mean standard error of calibration (RMSEC) and root mean standard error of cross validation (RMSECV) values obtained from PLS analysis were used to analyze the performance of the dielectric sensor. RMSEC is a measure of variability in the readings of the particle counter that is not explained by the model developed using calibrated data sets, while RMSECV is an indication of the predictive performance of the sensor, in the absence of an independent data set.

Results and Discussion

The plots for two different sizes of the rods obtained using PLS regression are shown in figure 5.

![Figure 5. Predicted adjusted ISO Code vs measured adjusted ISO code of the central rods with small diameter (left) and larger diameter (right). The green line represents the calibrated model and red line represents cross-validated model.](image)

The calibrated and cross-validated models obtained using PLS showed that the dielectric sensor was able to capture the increase in levels of iron contaminants in the hydraulic fluid. However, RMSEC and RMSECV values (Table 1) for the two rod sizes show that the sensor was more effective in measuring contaminants when larger diameter central rod was used. This was expected because larger diameter rod had lesser influence on sensing due to stray capacitances of electrical connections than the smaller diameter rod.

<table>
<thead>
<tr>
<th>Central rod diameter (inches)</th>
<th>Number of latent variables used</th>
<th>RMSEC (adjusted ISO code)</th>
<th>RMSECV (adjusted ISO code)</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>11</td>
<td>1.14</td>
<td>1.39</td>
<td>0.74</td>
</tr>
<tr>
<td>0.70</td>
<td>15</td>
<td>0.62</td>
<td>0.77</td>
<td>0.93</td>
</tr>
</tbody>
</table>

The PLS models were chosen based on number of latent variables that minimized the RMSECV value. The additional latent values could have resulted in a model overfitting the data. For both models slightly higher numbers of latent variables were required to explain the variation in the response. These models also excluded the data that represented very low contamination of hydraulic fluids (Low ISO code level). At this level of contamination several factors could affect the response of the dielectric sensor. Further, it should be realized that the sensor was not measuring static sample, rather flowing hydraulic fluid with varying amount of iron particles. Nevertheless it was able to capture this variation in the contamination level as verified by the results from PLS analysis. This performance suggests that the dielectric sensor could be used to classify the measuring hydraulic fluid into low and high metallic contamination levels.
Conclusions
From this research, it can be concluded that:

1. A low cost dielectric sensor can be used to effectively estimate contamination levels of hydraulic fluids containing iron particles and flowing through the sensor.
2. The dielectric sensor could be used for the classification of metal contaminated hydraulic fluids

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References


