

Dielectric spectroscopic sensor for particle contaminant detection in hydraulic fluids

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ABSTRACT

A practical contaminant sensor was developed that used dielectric spectroscopy to estimate levels of particles in hydraulic fluids. This dielectric sensor was designed for installation on off-highway vehicles to provide on-line estimates of hydraulic fluid cleanliness. Tests were performed using iron powder and ISO test dust as hydraulic fluid contaminants to investigate the performance of the sensor. An eight-channel particle counter was used for calibration of the dielectric sensor. Partial least squares regression models were developed to investigate the relationship between dielectric spectra and contaminant particle counts. The root mean square error of calibration (RMSEC) and root mean square error of cross validation (RMSECV) for the sensor with a central rod diameter of 6.35 mm were 1.1 and 1.39 of adjusted ISO fluid cleanliness codes, respectively, for iron powder. For a 17.7 mm diameter central rod, the respective RMSEC and RMSECV values were 0.62 and 0.83 for iron powder, and 1.29 and 1.48 for ISO test dust. The hydraulic fluid cleanliness level relative to particular particle contaminants can be determined by continuously monitoring fluid properties. The sensor shows good potential for estimating the cleanliness level of hydraulic fluid in the context of particle contaminants.

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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. High levels of contamination in the fluid could not only reduce efficiency of the hydraulic system but also lead to system failure. In fact, about 70% of all hydraulic system failures are due to contaminants in the fluid (Singh *et al.* 2012). Increasing contamination levels and changes in fluid properties could provide clues to potential failures of hydraulic components. A sensor capable of continuously monitoring fluid condition during equipment operation could prevent these components from possible damages, and thus avoid major financial loss.

Hydraulic fluid condition can be determined by measuring fluid viscosity, refractive index, density, base number, acid number, 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 and Hayzen 2001). This change in quality could be due to oxidation and depletion of additives. 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 of the fluid (Perez and Hadfield 2011).

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 complex relative permittivity, $\epsilon_r = \epsilon'_r - j\epsilon''_r$, where the real part ϵ'_r denotes the dielectric constant of the material and the imaginary part ϵ''_r denotes the dielectric loss factor. The dielectric constant of a material is a measure of its ability to store electrical energy; while the loss factor is a measure of energy lost in the 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 1954). Dielectric spectroscopy has been used for comparing different petroleum fractions (Tjomslund *et al.* 1996, Folgero 1998) sensing moisture dynamics in oil impregnated pressboard (Sheiretov and Zahn 1995), and monitoring of moisture content and insulation degradation in oil transformers (Koch and Feser 2004).

Particle counting is one of the techniques used for measuring particle contaminants in a hydraulic fluid. Commercially available automatic particle counters (APC) sense light blockage by solid particles and use

the ISO fluid cleanliness code (ISO 4406:1999) to report the contamination level in the fluid. The ISO fluid cleanliness code standard provides a standard means for reporting particle count data by converting the numbers of particles into broad classes or codes based on particle sizes. The reported code is expressed in a three number format; for example, 22/18/13. The first, second and third scale numbers, separated by slashes, represent a logarithmic scale related to the number of particles equal to or larger than 4, 6, and 14 μm , respectively, in 1 ml of fluid (ISO 4406:1999).

The volume of particles in a fluid can influence its dielectric properties. According to Maxwell Garnett's mixing rule, the effective permittivity of a mixture depends on the permittivity of its constituents, temperature and volume fraction of the particles in the host medium (Sihvola 2000). This relationship between permittivity and volume fraction enables development of dielectric sensor that could be calibrated with APC to measure fluid contamination. Furthermore, dielectric measurement is a relatively inexpensive technique that could provide a lower cost alternate for measuring contaminants in mobile applications.

The dielectric property of the fluid such as relative permittivity cannot be measured directly, but it can be measured through parameters of a circuit such as impedance (Z) or admittance (Y). These parameters can be easily measured using electrical instruments. Impedance is defined as the total opposition of an electrical circuit or device to alternating current (AC) at a given frequency. While admittance is the reciprocal of impedance and is given by $Y = G + jB$, where the real part (G) is conductance and the imaginary part (B) is susceptance. Conductance is associated with losses in the dielectric material and is expressed as $G = 2\pi f C_0 \epsilon''$, where f is the frequency of the sinusoidal excitation signal and C_0 is the capacitance of an empty capacitor with free space as the dielectric. Similarly, susceptance is the measure of polarisability and is associated with the energy storage capacity of the dielectric. For a capacitive form of the material, susceptance can be written as $B_c = 2\pi f C_0 \epsilon'$.

Partial least squares (PLS) regression is a supervised modeling technique that can be used to understand the relationship between the contamination level of the fluid and its dielectric properties. PLS operates by identifying a new set of independent variables called latent variables that are linear combinations of the original independent (predictor) variables and explain the most correlation between the response and the predictors. It is a dimension reduction method, which eliminates problems related to multicollinearity of the predictor variables and helps avoid over-fitting of the data (Abdi 2010). Hence, it is particularly useful if the number of independent variables describing the response variables is greater than the number of observations. The root mean square error of calibration (RMSEC) and root mean square error of cross validation (RMSECV) values obtained from the

analysis can be used as assessment tool for the model. RMSEC is a measure of variability in the response that the model failed to explain, while RMSECV is an indication of the predictive performance of the sensor, in the absence of an independent data-set, that is obtained using cross-validation.

The objective of this research was to build a capacitive sensor and investigate its ability to estimate the levels of iron particles and ISO test dust in a moving hydraulic fluid using dielectric spectroscopy measurement technique. The sensor was designed to be low cost for off-road vehicle installation and to provide in-line measurements of contaminants during operation.

Materials and methods

Hydraulic circuits were developed to determine dielectric sensor performance. Dielectric properties of the hydraulic fluids in the sensor were acquired by measuring conductance and susceptance using an impedance analyser (model 4192 LF, Hewlett-Packard, Palo Alto, CA, U.S.A.) connected to the dielectric sensor. These measurements were acquired over a 5 Hz to 13 MHz frequency range. Finally, PLS regression 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 grounding the case during measurements. The external dimensions of the sensor housing after assembly were 190.5 mm \times 101.6 mm \times 101.6 mm.

The shield and electrode assembly (Figure 2) that constitute the sensing unit was designed 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 (Figure 3) that were fabricated to allow passage of fluid through the sensor. 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 the outer conductor and central rod form the two main electrodes of the capacitive sensing unit. The outer conductor was connected to a short coaxial cable for receiving electrical input signals; while the central rod, lying inside and

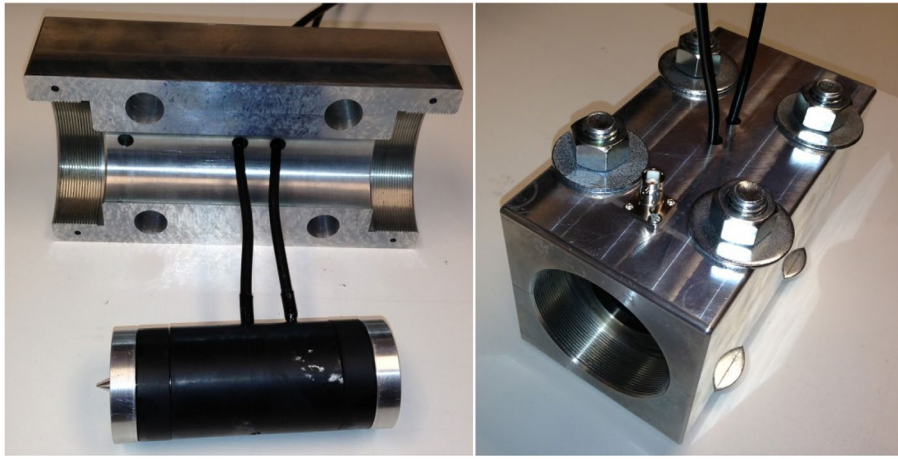


Figure 1. Sensor split housing design enables the assembly of the sensing unit and connection to cables (left) and complete assembly of the sensor (right).

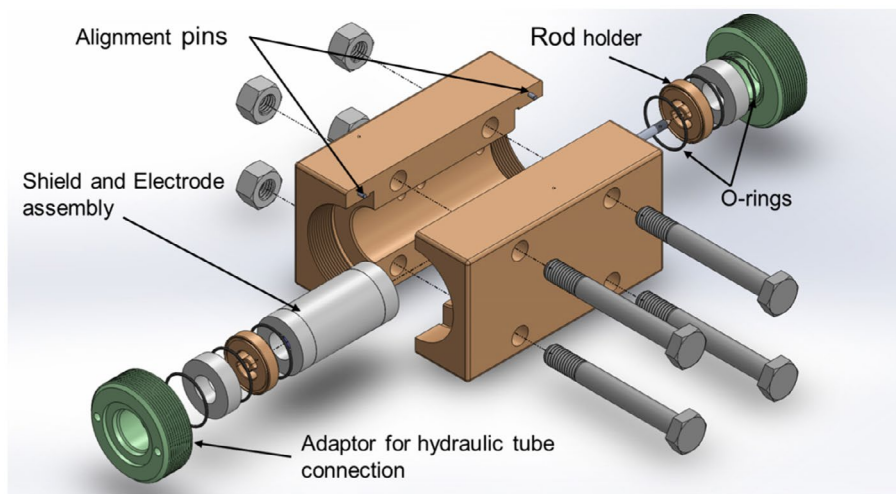


Figure 2. Exploded view showing flow-through design of the sensor and arrangement of different metallic parts and dielectric assembled.

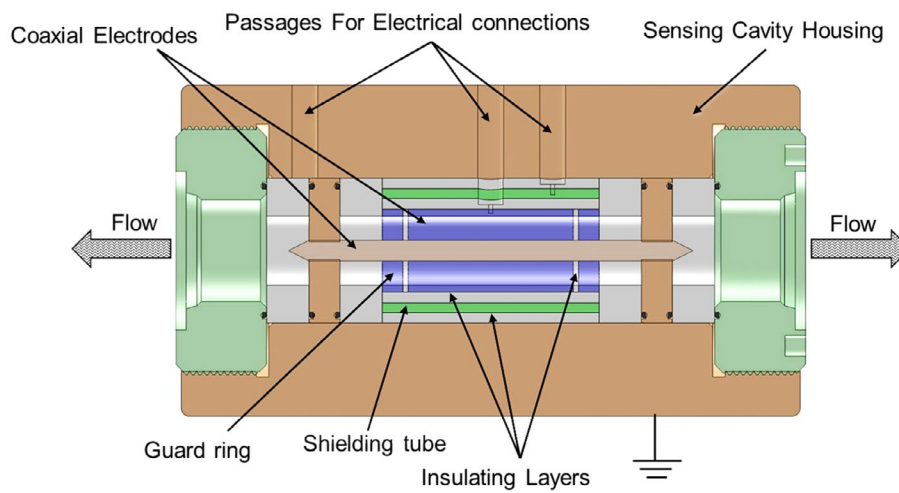


Figure 3. Cutaway view of the sensor housing shows the housing as well as the coaxial sensing unit with different metallic and dielectric parts.

coaxial to the outer conductor, was electrically grounded through metallic rod holders that made 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 a dielectric and has direct influence on the capacitance of the sensor.

The diameter of the outer conductor was chosen to match with that of the hydraulic connector to promote laminar fluid flow. A nominal 1-inch internal diameter (-16) SAE O-Ring Boss hydraulic connection was selected to ease manufacturability and minimise pressure drop. The central rod was designed with gradually tapering ends to maintain steady fluid flow through the sensing unit.

On either side of the outer conductor, two metallic guard rings (Figure 3) were placed coaxially and separated from the outer conductor by thin dielectric rings. These rings were used to minimise fringe effects from the edges of the outer conductor, and thus, focus the electric flux on the fluid in the sensing volume. The outer conductor and guard rings were surrounded by a tubular metallic layer called a shield. 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. A short coaxial cable was attached to the shield to maintain it at the same voltage as the outer conductor.

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 low to high frequencies, and compatibility

with oil. Hydraulic adapters were machined to fit into the threaded portion of the housing.

Hydraulic test circuits

The hydraulic circuits developed to test the dielectric sensor consisted of a fluid cleaning circuit and a test circuit (Figure 4). In general, the hydraulic fluid in an oil drum comes from the manufacturer with particle contaminants. Therefore, the fluid cleaning circuit (Figure 4(a)) was used to clean the hydraulic fluid before it was introduced into the test circuit (4b). The fluid cleaning circuit consisted of two filters (model Ultipleat® UE219AN08H, Pall Corp, Port Washington, NY and model SP15/25 P/N P564967, Donaldson, Bloomington, Minn.) 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 dose of iron particles with the clean fluid, while the other was used to store clean fluid used for testing.

Peristaltic pumps were selected to move the fluid in the circuit because they would not introduce additional wear particles into the test circuit. 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 (model ICM, Mpfiltri, Quakertown, PA) was added in the test circuit. Shut off valves and check valves were used to achieve desired flow operation required during the experiment.

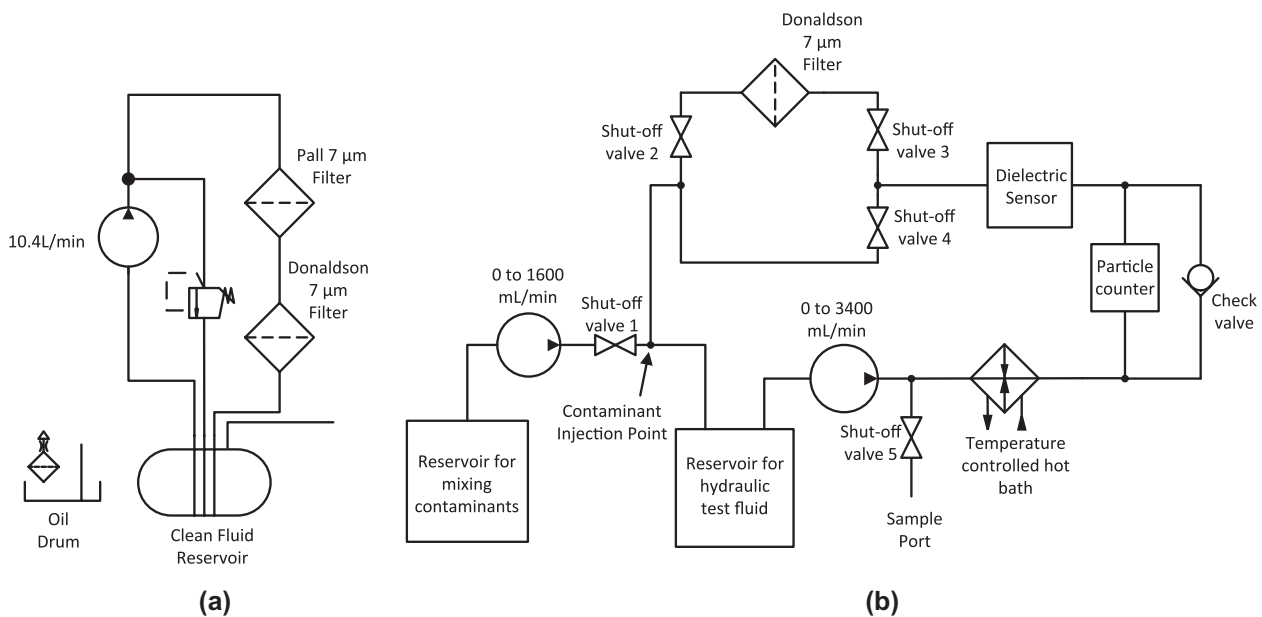


Figure 4. The test circuits consisted of (a) fluid cleaning circuit and (b) the sensor test circuit.

The presence of air bubbles in the hydraulic fluid can affect the experimental results. Therefore, to avoid air bubbles, a peristaltic pump was used and the tests were conducted at low pressure. In addition, the restriction between the pump and the reservoir was minimised to minimise the pressure drop, so that air was not pulled out of solution. During the tests, no visible air bubbles were observed, which was also confirmed by the results obtained from the APC. The APC is sensitive to air bubbles and would display abnormal readings if air bubbles pass through it.

Test procedure

Three tests were performed with solid particles as hydraulic contaminants. The initial two tests were performed with iron powder using the central rods of different diameters. The first test was performed using the rod diameter of 6.35 mm (0.25 inch). This diameter was initially considered in the research for impedance matching of the dielectric sensor with electrical source to maximise electrical power transfer. However, after realising 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 (0.70 inch) to determine if it would improve the sensing performance. The third test was performed with ISO test dust using the larger rod diameter. The capacitance of the sensor was calculated using the Equation (1):

$$C = \frac{2\pi\epsilon_{\text{oil}}\epsilon_o L}{\ln\left(\frac{b}{a}\right)} \quad (1)$$

where L is length of the outer electrode, ϵ_{oil} is the relative permittivity of the hydraulic oil, ϵ_o is the permittivity of the free space ($8.854 \times 10^{-12} \text{ F m}^{-1}$), b is the inner diameter of the outer electrode, and a is the outer diameter of the central rod. The capacitances of the sensor using the two different rod sizes and ϵ_{oil} of 2.1 are given in Table 1.

Iron powder (CAS: 7439-89-6; P/N 00170, Alfa Aesar, Ward Hill, MA) used in the test consisted of spherical iron particles less than 10 μm in diameter. The ISO medium test dust (ISO 12103-1, A3 medium, Powder Technology Inc., Burnsville, Minn.) had mixtures of chemical particles such as SiO_2 , Al_2O_3 , Fe_2O_3 , Na_2O , CaO , MgO , TiO_2 , and K_2O . Based on the data, regarding distribution of these particles in the mixture, the average size of the particles was found to be between 25 and 28 μm in diameter. The hydraulic fluid used during

the test was an ISO VG 46 hydraulic oil (Tellus, Shell, Houston, TX). Prior to each test, 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 test particles to produce a highly concentrated contaminant fluid mixture. In the test circuit reservoir, 2000 ml of clean hydraulic fluid was stored as the test fluid. This fluid was continuously stirred using magnetic stirrer to minimise settling of the particle contaminants. The temperature controlled hot bath maintained a steady fluid temperature of approximately 34 $^\circ\text{C}$ throughout the tests. The electrical terminals of the dielectric sensor were connected to the impedance analyser.

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 the temperature and cleanliness level reached a steady state. Clean fluid at the base level was the first sample measured using the impedance analyser. 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 reached steady state, dielectric measurements were acquired from this new sample test fluid. 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 maintain independent experimental replications, 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 acquire measurements from the dielectric sensor, the impedance analyser was programmed to measure both conductance and susceptance at 63 frequencies ranging from 5 to 13 MHz sampled linearly within decades. These dielectric spectroscopic measurements were acquired three times for each sample. At the same time, particle count measurements were acquired over 60 s time intervals, usually resulting in acquisition of nine particle count samples while the dielectric measurements were being acquired.

Data analysis

After the completion of the tests, PLS regression was used to develop multivariate models relating spectral measurements to particle counts from the particle counter. The ISO 4406:1999 cleanliness code from the particle counter was not directly correlated with the spectral data. The dielectric sensor measured bulk dielectric properties of the fluid, as a result larger individual particles would have greater influence on dielectric response of the sensor because of their ability to displace a larger fluid volume than smaller particles. Therefore,

Table 1. Dimensions and capacitances of the coaxial dielectric sensor.

Central rod diameter (mm)	Outer conductor diameter (mm)	Outer conductor length (mm)	Capacitance (pF)
6.35	21.4	50.8	4.88
17.7	21.4	50.8	31.3

Table 2. ISO code range and parameters used for developing adjusted ISO cleanliness code.

Measurement range index	Measurement range (μm)	Mean diameter in range X (μm)	Volume V_x (μm^3)	Relative multiplier $V_{X_i, \text{wrt. } 5\mu\text{m}}$
1	4–6	5	65	1
2	6–14	10	524	8
3	14–21	17.5	2806	43
4	21–25	23	6371	97
5	25–38	31.5	16,365	250
6	38–50	44	44,602	681
7	50–68	59	107,539	1643

a weighted composite cleanliness code was developed using the data from the particle counter. To develop this weighted code, ranges of particle sizes were selected to form equivalent ISO code ranges, shown as the measurement ranges in Table 2, using particle sizes reading from the eight measurement channels of the particle counter (>4, 6, 14, 21, 25, 38, 50, 68 μm (c)). The volume of the mean-sized particles in the range was calculated and a relative multiplier was developed using 5 μm as reference particle size (Equation (2)). The relative multiplier represent the quantity of 5 μm particles that would be needed to produce different volumes of mean-sized particles in ISO code range (Table 2) when combined together.

If X_i denotes any mean diameter in the ISO code range, then the relative multiplier, $V_{X_i, \text{wrt. } 5\mu\text{m}}$, for particular volume of mean diameter particle (V_{X_i}) can be written as:

$$V_{X_i, \text{wrt. } 5\mu\text{m}} = \frac{V_{X_i}}{5\mu\text{m}} \quad (2)$$

where $V_{5\mu\text{m}}$ is the volume of a 5 μm sphere.

If (n_1, n_2, \dots, n_7) denote the particle counts associated with the particle counter channels, the volume weighted count, V_{wc} , can be written as:

$$V_{wc} = \sum_{i=1}^7 n_i V_{X_i, \text{wrt. } 5\mu\text{m}} \quad (3)$$

This calculation generated a value that was approximately equal to number of 5 μm particles needed to make up the total particle volume detected by the particle counter.

For PLS analysis, particle counts corresponding to first ISO code range (>4 μm) was used for regression with spectral data. Since the count for this range from particle counter does not represent the actual volume of particles flowing through the sensor, a ratio was developed representing the contribution of the count in this range to the volume weighted count. The ratio for any sample in a test, R_m , is given as below:

$$R_m = \frac{n_1}{v_{wc_m}} \quad (4)$$

where n_1 represent the count of particle sizes from 4 to 6 μm from the particle counter in 100 ml of a sample. Here subscript m represent index for any sample in the

test. Hence, R_m is the ratio for a sample with volume weighted count of V_{wc_m} .

Since the contribution of the count at this range differed for different samples (contamination level reading) in the test, an average of the ratio was calculated from all the samples in the test (Equation (5)), and the adjusted volume weighted count, $V_{adj_count_m}$ for each sample was calculated by multiplying the mean ratio with its volume-weighted count (Equation (6)).

$$R_{\text{avg}} = \frac{\sum_{m=1}^{N_{\text{obs}}} R_m}{N_{\text{obs}}} \quad (5)$$

where N_{obs} represent the total number of samples in all three replications for a test

$$V_{\text{adj_count}} = R_{\text{avg}} V_{wc_m} \quad (6)$$

ISO code models are developed based on the base-two logarithmic relationship between the ISO codes and the particle counts represented in the equation. Therefore, the adjusted ISO code, $C_{\text{adj_ISO}_m}$, developed for the analysis can be written as:

$$C_{\text{adj_ISO}_m} = \log_2 \left(V_{\text{adj_count}_m} \right) \quad (7)$$

PLS models were finally developed using $C_{\text{adj_ISO}_m}$ as the response variables and dielectric measurements as the predictors variables. Cross validation was performed to assess the predictive ability of the models. RMSEC and RMSECV values obtained from PLS analysis were used to analyse the performance of the dielectric sensor. For the model, volume fractions of contaminants to oil could also have been used instead of using the adjusted ISO code. The volume fractions of contaminant particles to oil for samples with lowest and highest level of contaminants were found to be in the range of 6.46×10^{-7} and 2.06×10^{-3} respectively. These very small volume fraction values correspond to 14 and 25 ISO code cleanliness levels for particle sizes in the 4–6 μm range. However, these fractions were not used because ISO cleanliness code is more commonly used than volume fraction to indicate the contamination level of hydraulic fluids. So to better communicate with the readers a volume fraction adjusted 4–6 μm ISO cleanliness code for model calibration was developed and used.

Moreover, other than contaminant particles, oil degradation can also affect dielectric constant of the hydraulic fluid. Dielectric spectroscopy uses multivariate

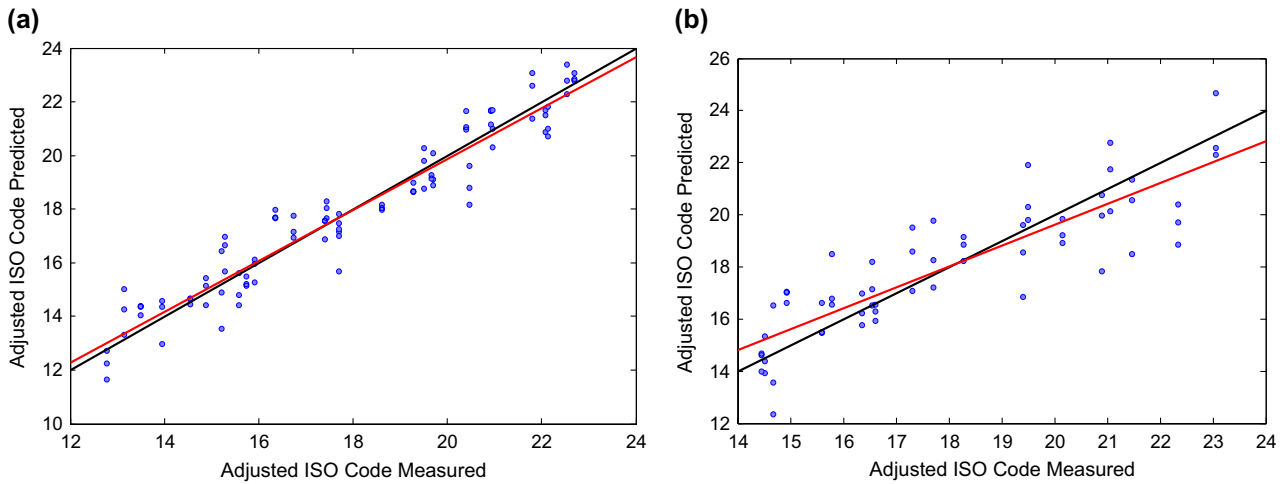


Figure 5. Predicted adjusted ISO Code against measured adjusted ISO code for the PLS cross-validation models developed using central rods of diameter (a) 17.7 mm and (b) 6.35 mm using iron powder as test contaminants. The black line represents 1 to 1 line and red line represents regression line for cross-validated model.

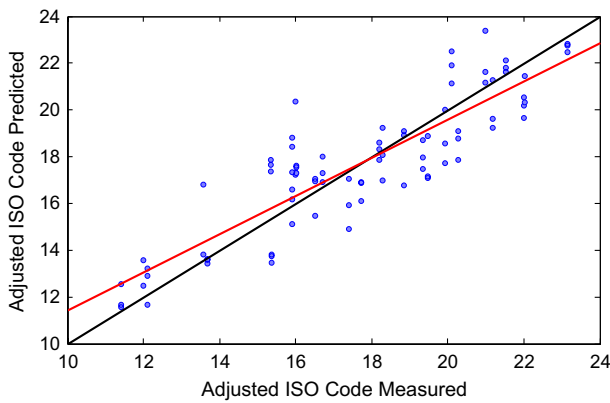


Figure 6. Predicted adjusted ISO Code vs measured adjusted ISO code for the ISO test dust PLS model. The black line represents the 1 to 1 line and red line represents regression line for cross-validated model.

statistics with many independent predictor variables allowing development of different PLS models for different types of response variables. As a result, predictive models could also have been developed for oil degradation metrics; however, for the scope of this research project, the objective was to develop models that predict the particle contamination level in hydraulic fluid.

Results and discussion

The calibrated and cross-validated models obtained using PLS (Figures 5 and 6) showed that the dielectric sensor was able to capture increases in the levels of iron particles and ISO test dust in the hydraulic fluid.

There was less variation in the data for the test with the 17.7 mm diameter central rod as seen in Figure 5(a), while the more variability was observed in the data associated with the 6.35 mm central rod using iron powder (Figure 5(b)) and the 17.7 mm diameter rod with ISO test dust particles (Figure 6). These results show that the dielectric sensor was more sensitive in measuring iron powder in the hydraulic fluid when the 17.7 mm diameter central rod was used.

The models in the PLS regression were selected based on the number of latent variables that minimised the RMSECV value. The use of additional latent variables could have resulted in a model that would overfit the data. The test results obtained from three tests are based on the selection of different latent variables that can be seen in Table 3. For the test performed with central rod of 17.7 mm in diameter and iron powder as contaminants, the RMSEC and RMSECV values were observed to be 0.62 and 0.83 respectively based on 16 latent variables. This shows that the calibration model obtained using larger rod was able to detect iron contaminants within ± 0.62 of the adjusted ISO code level, while for cross validation the result was found to be within ± 0.83 of the adjusted ISO code (Table 3).

Similarly, RMSEC and RMSECV values for 6.35 mm central rod were 1.1 and 1.39 for the test with iron powder after selecting nine latent variables. The results for the smaller rod were not as good as those obtained for the larger rod, as the prediction results for the calibration and cross-validation were found to be greater than 1 adjusted ISO code level. These results show that the dielectric

Table 3. PLS calibration and cross-validation results for two central rods.

Particle contaminants	Central rod diameter (mm)	Number of latent variables	RMSEC (adjusted ISO code)	RMSECV (adjusted ISO code)	R^2
Iron powder	6.35	9	1.1	1.39	0.7
Iron powder	17.7	16	0.62	0.83	0.923
ISO test dust	17.7	9	1.29	1.48	0.78

sensor had better accuracy in measuring contaminants with larger diameter central rod. The accuracy improved for the larger rod diameter possibly because the dielectric measurements were less affected by stray capacitances due to higher capacitive value (31.3 pF) of the larger diameter rod. On contrary, the smaller diameter rod had a capacitance of 4.88 pF which may have been dominated by stray capacitances from other electrical components.

Further, the electric field strength (E) can be expressed as:

$$E = \frac{\Delta V}{r \ln \left(\frac{b}{a} \right)} \quad (8)$$

where ΔV represents electric potential difference between two electrodes, r is the distance from the center of central electrode to some point between outer and central electrode, b is the inner diameter of the outer electrode, and a is the diameter of the central electrode. This equation shows that for some constant ΔV and any fixed distance r , E is higher for smaller ratio of b to a . Since the ratio is smaller when larger diameter rod is used, its electric field strength is higher and has greater capability to detect contaminants compared to the smaller diameter rod. Moreover, the distribution of electrical field strength between outer conductor and central rod is almost uniform when a larger diameter central rod is used. As a result, particles moving close to any of these electrodes will have an equal effect on the dielectric measurement. On contrary, with a smaller diameter rod, the radial electric field lines will be comparatively less concentrated at one end of the electrode, and hence will lead to unequal electric field strength at two ends. Thus, the sensor could become less responsive when the particles move closer to the electrode with lower electric field strength. This phenomenon may explain the greater variability in the data when the smaller diameter rod is used in comparison to the larger diameter rod in Figure 5.

The RMSEC was 1.29 and RMSECV was 1.48 for the test with ISO test dust conducted using the 17.7 mm diameter central rod. The calibration model detected ISO test dust particles within ± 1.29 of an adjusted ISO code level, and the prediction based on cross-validation was ± 1.48 . Based on these results, it can be inferred that the dielectric sensor was more sensitive to iron powder in the hydraulic fluid than ISO test dust particles. This effect was probably because the effective dielectric constant of the hydraulic fluid increased more with the very high dielectric constant of iron powder (almost infinite). On the contrary, ISO test dust consists of particles with dielectric constants similar to that of the hydraulic fluid. For example, dielectric constant of silica (SiO_2), the major component of ISO test dust (68–76% of weight), is around 3.9, which is closer to the dielectric constant of typical hydraulic oil (2.1–2.4). Probably due to this similarity, the sensor was less responsive to the presence of the test dust contaminants.

Unlike laboratory sampling techniques that measure static fluid samples to determine contamination level in a hydraulic fluid, the dielectric sensor measured solid contaminants in a moving fluid. The number of these contaminants may fluctuate considerably in the moving fluid even for the same ISO code level. However, the sensor was able to successfully capture this variation across a wide range of fluid contamination, as verified by the results from PLS analysis. To develop PLS models for all three tests, nine or more latent variables were required, mostly to capture variations in the particle count obtained using the particle counter. Further, since these counts fluctuated substantially at low contamination level, the data associated with these counts were not used to develop the models. The dielectric measurements at this level may also be more variable due to the very small number of particle contaminants associated with low ISO code ranges.

Conclusions

From this research, the following conclusions can be drawn:

- (1) Dielectric spectroscopy has good potential to detect particle contaminants in a flowing hydraulic fluid at levels that are consistent with modern hydraulic components.
- (2) Dielectric spectroscopy can also be used to predict levels of completely different types of particles such as metals and dust in the hydraulic fluids using prediction models developed for those particles.
- (3) For all the particles used in the tests, it was found that the dielectric sensor has very good potential to classify the hydraulic fluid with low and high level of contaminants.

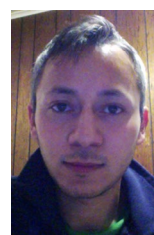
Disclosure statement

No potential conflict of interest was reported by the authors.

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