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Development of an instrumentation system for measurement of degradation of lubricating oil using optical fiber sensor

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ABSTRACT

This paper presents an instrumentation system to measure the degradation in lubricating oil using a bare, tapered and bent multi-mode optical fiber (BTBMOF) sensor probe and a temperature probe. The sensor system consists of (i) a bare, tapered and bent multi-mode optical fiber (BTBMOF) as optical sensor along with a laser source and a LDR (Light Dependent Resistor) as detector (ii) a temperature sensor (iii) a ATmega microcontroller based data acquisition system and (iv) a trained ANN for processing and calibration. The BTBMOF sensor and the temperature sensor are used to provide the measure of refractive index (RI) and the temperature of a lubricating oil sample. A microcontroller based instrumentation system with trained ANN algorithm has been developed to determine the degradation of the lubricating oil sample by sampling the readings of the optical fiber sensor, and the temperature sensor.

1. Introduction

Lubricating oil is a dielectric material with low losses and employed in internal combustion engines for reducing the frictions of the mobile components while keeping the different elements clean [1]. With prolong use, the dielectric property (or non-conducting) property of the oil degrades. Degraded lubricating oil may contain contaminants like water, soot particles, acid combustion products, glycol, ferrous and non-ferrous metallic particles. The degradation of most oils imply the generation of molecules that are generally more polarized than the large hydrocarbon molecules which are weakly polarized.

Lubricating oils are exposed to various strains depending on the operating conditions, the fuel quality, the ambient conditions and operating parameters and the rate of deterioration of lubricating oils strongly depends on all these factors. At the same time unnecessary oil change should be curtained in order for environmental effect and economic reason [2]. Hence it is necessary to monitor the degradation of engine oil so that the oil could be removed when dilapidated. The degradation of lubricating oil is measured by several methods. One of the common method of detection of contamination in lubricant oil and estimation of its quality is by observing the change in value of dielectric constant when different oil samples is placed as dielectric medium in capacitive sensor [3]. Lubricant oil degradation is also measured by other techniques like testing of oil in Hall Effect sensor [4], dielectric spectroscopy [1], Timken method [5] etc.

The polarizability of lubricating oil is related to the RI of the oil sample by the Clausius–Mossotti relation [6]. Again the density, polarizability and dipole moment of lubricating oil is related to the dielectric constant by the Debye equation [7].

Since $\varepsilon_r = n_l^2$, (as shown by the Clausius–Mossotti equation) [6], where ε_r is the dielectric constant and n_l is the refractive index, the relation of RI with temperature, polarizability, dipole moment, density, molecular mass and kinematic viscosity (as given in the Debye equation and Clausius–Mossotti relation), can be used for finding the degradation of lubricating oil.

One of the common methods of measuring the RI of a material is the use of a refractometer [8,9]. Optical fiber refractometer has been used in the simultaneous analysis of RI and temperature [10].

This paper describes an instrumentation system to measure the degradation of lubricating oil using an optical fiber sensor probe (OFSP), whose sensing element is a BTBMOF and a temperature sensor. To prepare the BTBMOF, a length measuring 45 mm around the center of a multi-mode optical fiber is made open by removing the plastic jacket and then the method as described in [9] is used. After following the procedure the length of the BTBMOF was made approximately 47 mm. The bare and tapered portion of the optical fiber sensor is given a shape of a semicircular arc of fixed radius of curvature to add macro bending effect along with the power coupling effect. The BTBMOF is used to fabricate an optical sensor, using a diode laser source and a LDR as a detector. Laser beam from

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the diode laser source is launched at one end of the OFSP. The power transmitted through the bare, tapered and bent portion of the multi-mode optical fiber depends on the RI of the liquid applied around it. The laser beam propagates through the BTBMOF is incident on the surface of the LDR. The resistance value of the LDR changes according to the change in RI value of the liquid surrounding the BTBMOF. The LDR is connected across a 5 V supply with a series resistance to form a potential divider circuit. The output of the potential divider circuit changes according to the change in resistance of the LDR which is again a function of RI. A trained ANN is used to process and calibrate the input data. The parameters, such as weightage matrix elements and threshold of the trained ANN, are stored in the microcontroller flash memory to determine the degradation of lubricating oil sample using the input from the potential divider and temperature sensor IC.

2. Principle of bare, tapered and bent multi-mode refractometer

The BTBMOF is considered as the sensing element for the proposed microcontroller based instrumentation system to measure RI of a liquid. The bare and tapered portion of the optical fiber sensor is given a shape of a semicircular arc of fixed radius of curvature. The geometry of the proposed refractometer is shown in Fig. 1 [9].

From the geometry of the proposed sensor shown in Fig. 1, the expression of power associated with laser beam at the output end of the fiber for the BTBMOF portion of the OFSP when the bare tapered and bent portion of the OFSP is exposed to liquid medium has been derived [9] and is as shown

$$P(L)_l = P_0[K_1 - K_2 n_l^2][1 - 0.2304(K_3 - K_4 n_l^2) \exp\left\{-K_5(b - K_6 n_l^2 - K_7)^{3/2}\right\}] \tag{1}$$

where,

$$K_1 = \frac{n_1^2}{R^2(n_1^2 - n_{cl}^2)},\ K_2 = \frac{1}{R^2(n_1^2 - n_{cl}^2)},\ K_3 = \frac{2bn_1^2k_0L}{n_1},$$
$$K_4 = \frac{2bk_0L}{n_1},\ K_5 = \frac{2}{3}n_1k_0R',\ K_6 = \frac{b}{n_1^2} \text{ and } K_7 = \frac{2a_0}{R'}$$

α_B is the attenuation coefficient due to macro bending effect, L is the length of the bent portion of the BTBMOF and $P(L)_l$ is the power at the output end of the fiber for the BTBMOF portion of the OFSP and P_0 is the power coupled into the input end of the fiber, n_l is the RI of the medium around the bare, tapered and bent region of the OFSP respectively, R is the taper ratio $\left(= \frac{a_i}{a_0}\right)$, a_i and a_0 are the radius of the core in the untapered and tapered (and bent) region of the BTBMOF, n_1 and n_{cl} are the refractive index of the core and cladding respectively, R' is the radius of curvature of the tapered and bent portion of the BTBMOF, b is a constant ($0 \leqslant b \leqslant 1$ for a guided mode) and k_0 represent the wave propagation constant.

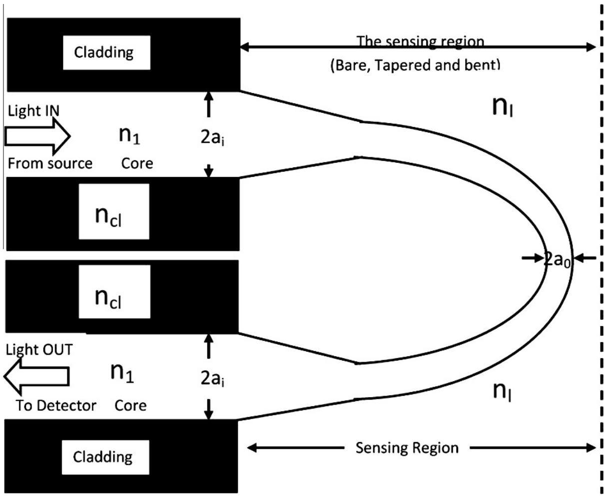

Fig. 1. The geometry of the proposed refractometer.

3. Relation between refractive index, viscosity and temperature

The relation between the macroscopic susceptibility x_e or dielectric constant ε_r and the microscopic polarizability α, of the molecules constituting the lubricating oil is given by the Clausius–Mossotti [6] relation as-

$$\alpha = \frac{3}{N}\left(\frac{\varepsilon_r - 1}{\varepsilon_r + 2}\right) \tag{2}$$

where ε_r is the permittivity (dielectric constant) of the oil, α is the polarizability and N is the number of molecules per unit volume.

Again we have

$$\frac{n^2 - 1}{n^2 + 2} = \frac{1}{3}\sum_i n_i\alpha_i \tag{3}$$

where n is the refractive index of the oil and $n^2 = \varepsilon_r$.

$N\alpha = \sum_i n_i\alpha_i$ represent that the individual polarizabilities *are additive*.

Eq. (3) is called the Lorenz–Lorentz relation.

Eq. (3) is further modified as-

$$\frac{M}{\rho}\frac{n^2 - 1}{n^2 + 2} = \frac{1}{3}A\alpha$$

$$\text{Therefore,}\quad \frac{n^2 - 1}{n^2 + 2} = \frac{A\rho\alpha}{3M} \tag{4}$$

where A is the Avogadro's number (6.02×10^{23} molecules of oil/mole), ρ is the density of the oil (gram/cm^3) and M is the molecular weight of the oil (gram/mole).

According to Stokes–Einstein relation,

$$\mu_0 \propto \rho = \vartheta_0\rho$$

$$\text{Therefore}\quad \rho = \frac{\mu_0}{\vartheta_0} \tag{5}$$

where μ_0 is the dynamic viscosity and ϑ_0 is the kinematic viscosity

Effects of temperature on solvent viscosity can be correlated by the following well-accepted empirical relation [11]

$$\mu_0 = A' \exp\frac{B}{T - T_0} \tag{6}$$

where A' and B are constants, T_0 is reference temperature and T is the absolute temperature in degree Kelvin.

Substituting Eqs. (5) and (6) in (4), we have

$$\frac{n^2 - 1}{n^2 + 2} = \frac{AA'\alpha_p}{3M\vartheta_0}\exp\frac{B}{T - T_0} \tag{7}$$

Taking $\frac{AA'\alpha}{3M\vartheta_0}\exp\frac{B}{T - T_0} = K_8$, Eq. (7) becomes

$$n^2 - 1 = K_8 \times (n^2 + 2)$$

$$\text{Or}\quad n^2 = (2K_8 + 1)(1 - K_8)^{-1}$$

$$\text{Or}\quad n^2 = 1 + 3K_8 + 3K_8^2 + 3K_8^3 + \cdots + 3K_8^{n+1} \tag{8}$$