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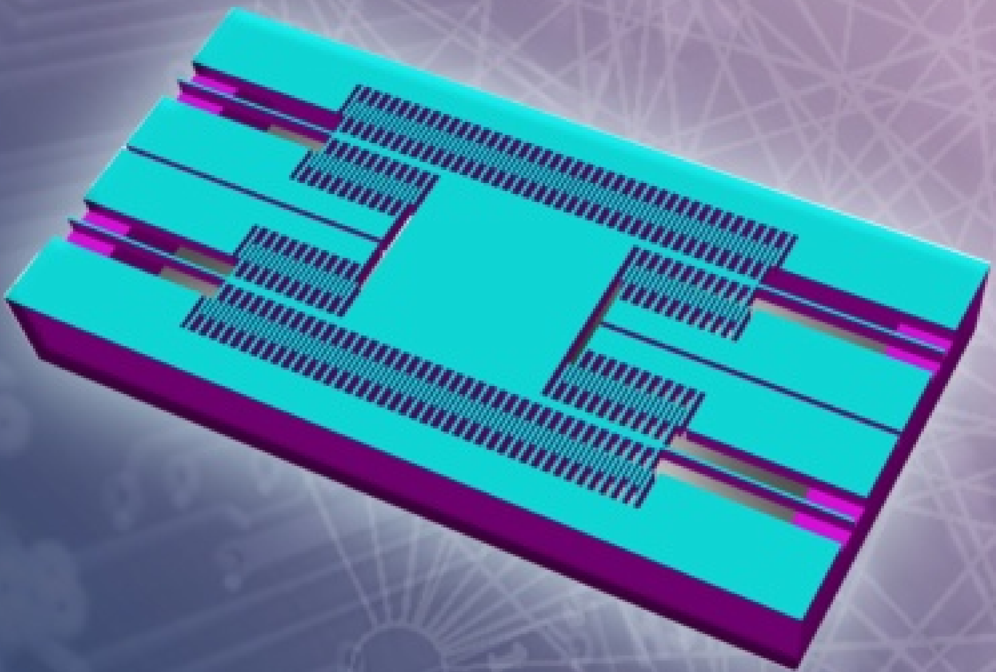

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Capability of Optical Approach in Condition Based Monitoring of Lubricant Oil

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Abstract: This paper presents the optical capability in monitoring the variation of light transmittance in the lubricant oil due to the oxidation by using Embedded MATLAB Function (EMF) tools. Recently, the increasing amount of used engine oil has been due to the car's manufacturer that recommended users to change their engine oil at a constant time or according to mileage interval. This will make a possibility of substantial increases of used engine oil because it changed more frequently than necessary. Therefore, a condition based technique is introduced to monitor the oxidation of lubricating engine oil by using EMF. By applying the regression analysis in EMF, the result shows that the slopes varied according to the degradation trends. Therefore, the capability of optical with combination of embedded tools to predict the degradation lifetime has been proven as compared to the others work that only analyzed the degraded condition without predict the future condition.

Keywords: Engine oil, Degradation, Regression, Embedded Matlab function.

1. Introduction

Engine oil operates as a lubricant for various internal moving parts at combustion engines in the vehicles [1]. It also performs to clean, reduce corrosion, improves sealing and cools up the engine. As the combustion parts keep moving, the lubricant will be degraded with relation to the temperature and time. Ineffective monitoring will result in increasing amounts of carboxylic acid whereas it produce varnishes and sludge that directly decreases the efficiency of the lubricant and reduces the performance of engine [2]. Total Acid Number, TAN (mg KOH/g), Total Base Number, TBN (mg KOH/g) and viscosity (Cst) are the type of chemical analysis in determining the oxidation level and contamination contents in lubricant that contributes to the lubricant degradation [3]. Recently, most engine oil changes have been conducted based on the recommendation by the vehicle manufacturers and service center. This situation will make the possibility that the engine oil is changed more frequently than necessary [4].

Online monitoring techniques have been introduced in many ways to alert the user about the suitable time to change their engine oil. A quantitative techniques were capable to predict the lubricant degradation, monitoring and classifying the engine operating parameters [5]. The data were taken using alumina plate sensor and plotted on the graph with the variation of voltage due to the usage of mileage. The other researcher, L. Guan et al. [6] uses Dielectric Spectroscopy (DS) to analyze the oxidation degradation process of engine lubricating oil qualitatively and quantitatively compared with Fourier Transform Infrared Spectroscopy (FTIR). Besides that, H. Bae Jun et al [7] introduces a new technique to predict the suitable change time of automotive engine oil by analyzing the degradation status using mission profile data. In developing a predictive maintenance algorithm for engine oil change, it is necessary to identify critical factors for detecting oil degradation status since several factors can affect the quality of engine oil during engine operations.

Recently, the optical approach became more useful for degradation monitoring. The ability of middle (MIR) and near (NIR) infrared range of spectroscopy to detect the chemical contents had encouraged more application in degradation monitoring technique. For example, A. R. Caneca [8] was applying qualitative and quantitative techniques for monitoring the condition of lubricating oils in diesel engines for near and middle infrared spectroscopy. The qualitative approach formulated in the context of pattern classification while the quantitative approach employs an IR spectroscopy and multivariate calibration techniques in order to predict viscosity, which is the main control parameter for lubricants in service. Therefore, the infrared spectroscopy measurement became the most effective technique in determining the degradation parameters of engine oil [1-3, 7, 8]. An optical color sensor with blue LED has been introduced in [9] to monitor the degradation of engine oil with critical limit determination. The result showed that the critical limit occurred at substantial decrease of light transmittability whereas the critical limit introduced in [10] was proven.

Even though there were a lot of techniques of lubricant monitoring and analysis have been done, it still lacked in determining the correct time to change the lubricant. Therefore, the more effective technique in monitoring the degradation parameters is required. This article discusses how the high linear correlation between the optical and chemical analysis from previous study [3] has been used to develop a new algorithm using EMF for monitoring and predicting the condition of engine oil. The oxidation was chosen as the main parameter because it influences the changes of the TAN and subsequently reduced the performance of the engine. By using this equation, the condition of engine oil due to oxidation can be monitored and predicted.

2. Spectroscopy Experiment

This experimental work requires more than 300 hours for getting many types of sample for analysis. The type of CD SAE 15W/40 engine oil was used for degradation monitoring where it has been baked at a certain time to get the chemical reaction for oxidation purposes. Because of the limitation of lubricant equipment facilities, the data have been donated by [11] and it has been extracted by using our Perkin Elmer equipment. Fig. 1 shows the data of spectroscopy measurement and labelled with oxidation wavelength. 4 locations have been identified to have maximum peak that influences the oxidation caused as discussed in [2]. The data also have the consistent sampling time at around 14 hours per sample that made the easier the analysis as shown in Table 1.

Warning limit of oxidation degradation that measured using optical spectroscopy has been investigated whereas it occurred when there was a substantial increase of absorbance when the light passed through the lubricant [10]. In this experiment, the % transmittance has been used in monitoring the oxidative degradation and the substantial decrease of transmittance has been recorded. We found that the substantial decrease of transmittance occurred at 33 % reduction from the new lubricant reading and it occurred at between *t+t7* and *t+t8*. According to the Table 1, it shows that the percentage of transmittance (%T) is reduced as the oxidation time increased. Therefore, the future oxidation condition can be predicted.

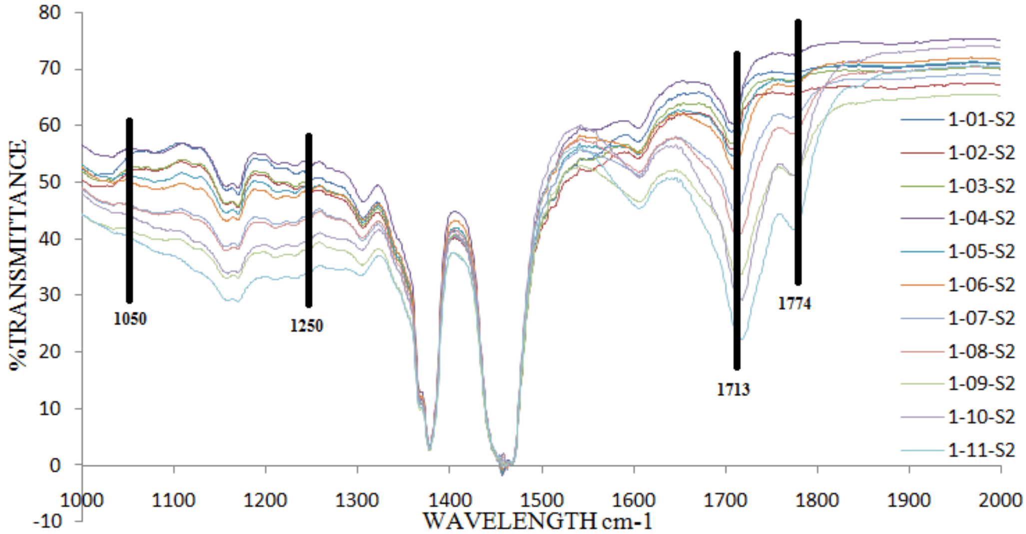

Fig. 1. Spectroscopic measurement for CD SAE 15W/40 engine oil.

Table 1. Extracted Data of Oxidation Band.

	Transmittance Peak Areas Of Oxidation (%)										
	t	**t+t1**	**t+t2**	**t+t3**	**t+t4**	**t+t5**	**t+t6**	**t+t7**	**t+t8**	**t+t9**	**t+t10**
Time / cm^{-1}	**11.14**	**25.12**	**38.43**	**51.25**	**65.12**	**79.27**	**92.08**	**106.25**	**120.25**	**133.88**	**149.08**
1050	54.75	51.86	52.46	55.92	51.42	50.24	46.10	45.97	41.57	44.27	40.42
1250	50.60	48.37	49.05	53.07	48.83	48.62	44.38	43.93	38.58	40.19	34.40
1713	61.35	57.93	58.98	62.31	56.1	53.06	44.85	40.32	33.25	29.53	22.80
1774	69.09	65.59	68	72.47	67.81	66.96	61.45	58.57	51.23	51.24	41.66

3. Linear Regression and Prediction Analysis

The analysis is started by storing the data into the Embedded Matlab Function. Then, the correlation and regression analysis between percentage transmittance of oxidation and time was analyzed and simulated in Simulink Matlab. The relationship between two variables in a regression analysis is expressed by a mathematical equation between two variables x and y is written as an equation (1);

$$y = \beta_0 + \beta_1 x \, , \tag{1}$$

where β_o is the intercept point of the regression line and m is the slope of the equation. The values of slope are described by equations (2).

Slope

$$(\beta_1) = \frac{SS_{xy}}{SS_{xx}} = m, \tag{2}$$

where:

$$SS_{xy} = \sum_{i=1}^{n} x_i y_i - \frac{(\sum_{i=1}^{n} x_i)(\sum_{i=1}^{n} y_i)}{n}$$
$$SS_{xx} = \sum_{i=1}^{n}(x_i - \bar{x})^2 = \sum_{i=1}^{n} x_i^{\,2} - \frac{(\sum_{i=1}^{n} x_i)^2}{n},$$

x_i = time;
y_i = variable of % transmittance;
m = the slope of the regression line y axis;
n = number of values or elements.

Based on the equation 1 and 2, the maximum limit of degradation can be determined depending on the value of the slope. The lifetime will be shorter when the slope is approaching to 100 % while the usage can be prolonged if the slope remains below 5 %. Regarding to past research, warning limit of the lubricant that measured by an optical spectrometer occurred when there was a substantial increase of absorbance for the light through the test material [10].

For prediction time equation, the Theorem Pythagoras shown in equation 3 has been applied as the calculation purposes.

$$\hat{x} - x_n = \frac{\hat{y} - y_n}{m}, \tag{3}$$

where:
$\hat{x}$ = the remaining time of lubricating engine oil before warning limit;
x_n = current running condition;
$\hat{y}$ = predicted of the future condition of % reflectance;
y_n = any input from current % transmittance.

Linear regression analysis was done at every 3 input data that taken from the optical sensor and controlled by programming as shown in flow chart at Fig. 2. The data count (DC) acted as a counter to ensure that the data taken at 3 times and reset to zero when it reached the target. Then, the regression analysis has been performed for data monitoring and prediction.

4. Embedded MATLAB Simulation

A simulation in real time analysis cannot be performed using MATLAB without additional external circuit. Therefore, the collected data in this work were analyzed frequently. The data became an input to the Embedded MATLAB Function for analysis by using an Algorithm as shown in Fig. 3.

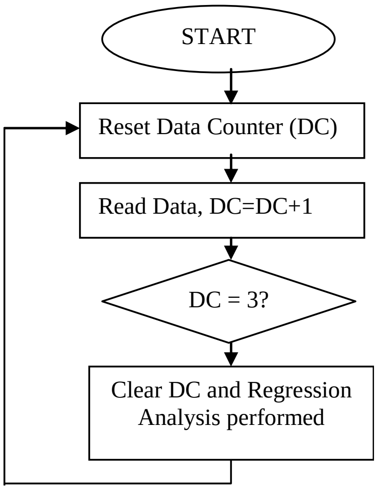

Fig. 2. Flow chart of data counter and regression analysis.

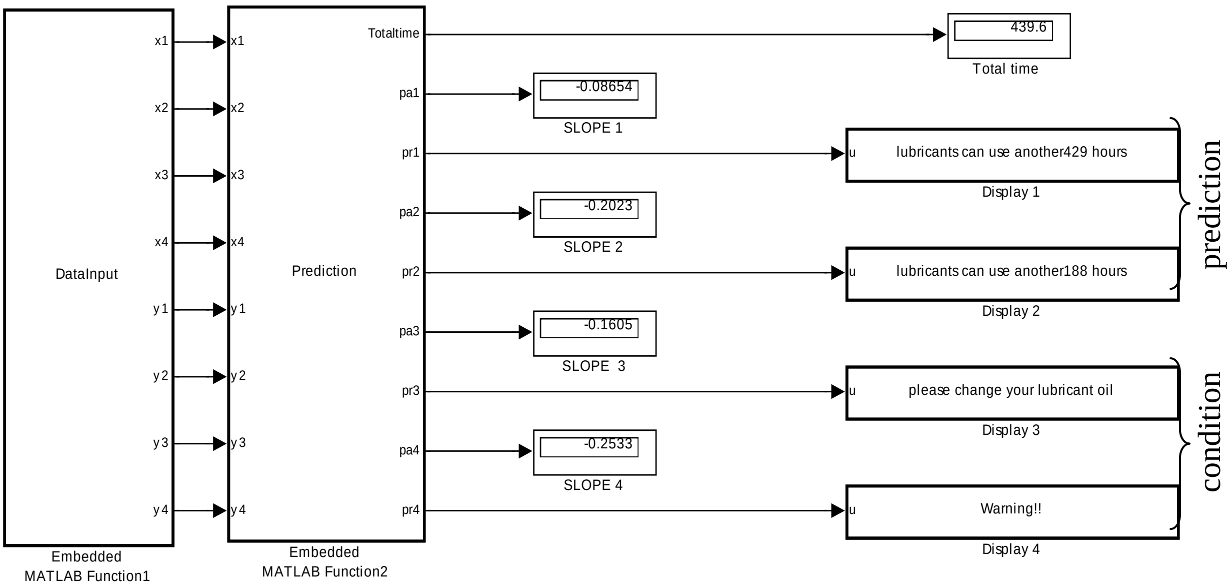

Fig. 3. Embedded block for monitoring the degradation of oxidation in lubricants by using Matlab Simulink.

The first embedded Matlab function block of the system is used to store data in an array from Simulink while the second block is used to write the coding for prediction and analysis. In this study, three types of environment usage were monitored and predicted. This algorithm would send out warning signals, such as “lubricant can use another 456 hours”, “please change your lubricant oil” and “warning” as an indicator of engine oil condition. Warning signal will be appearing in the display when the real time algorithm starts running. The warning signal will show the condition of lubricant degraded due to time variance. The first analysis is for “Short trip driving with new engine” which is considered the lubricant can stand up to 70 % from the virgin oil condition. The other analysis is done for 50 % and 15 % for the average user and worst case condition of old engines and aggressive driving style respectively.

Fig. (4-7) shows the graphs of the percentage transmittance of oxidation versus time for the different stage data in the transmittance peak area at band location 1050 cm^{-1}. A common first degree regression equation was developed by taking the average slope and interception point. Then, the values of each slope will be used for making the analysis of the total time for lubricant can be used. Fig. 7 shows the three different reference wavelengths which are about 15 %, 50 % and 70 % of three cases of environment usage. Fig. 8 and Fig. 9 show the graph of percentage transmittance oxidation in lubricating oil for band location 1250 cm^{-1} and 1713 cm^{-1} respectively. The value of reference wavelength for every case condition is used for making predictions of the lubricant usable lifetime.

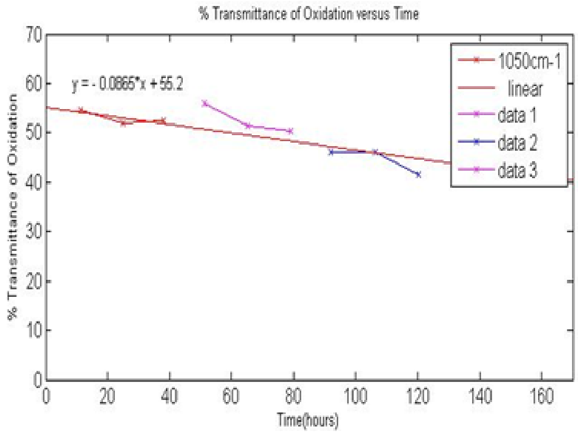

Fig. 4. Linear regression at 1st 3 data.

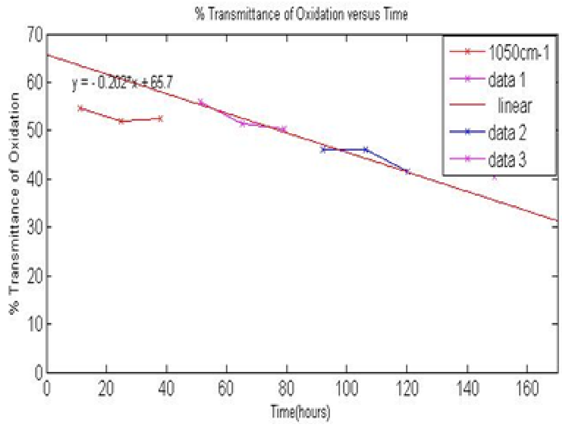

Fig. 5. Linear regression on 1st 3 data.

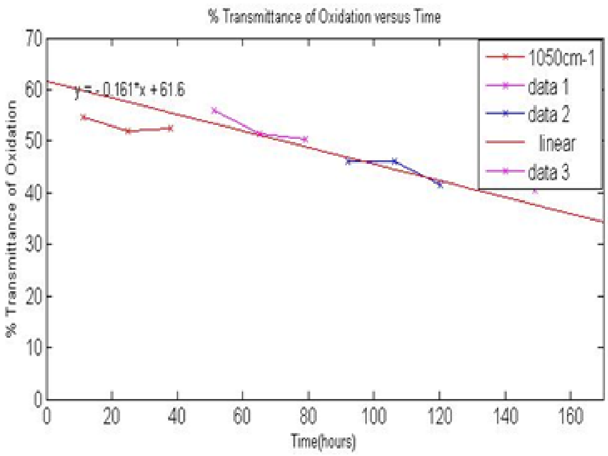

Fig. 6. Linear Regression at 3rd 3 data.

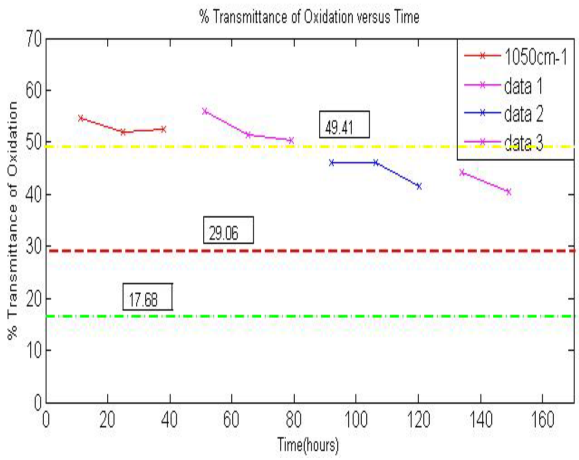

Fig. 7. Different percentages of degradation at 1050 cm^{-1}.

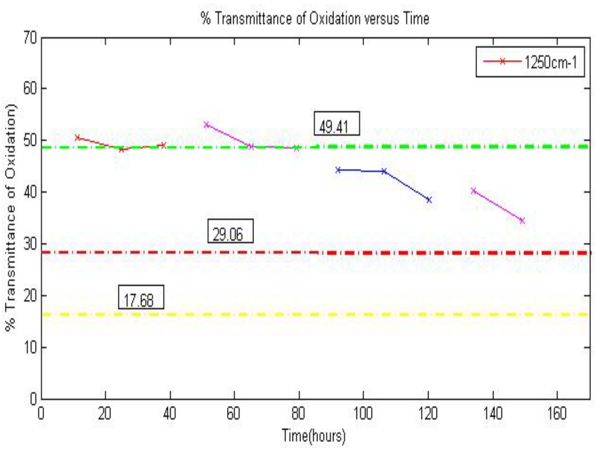

Fig. 8. Different percentages of degradation at 1050 cm^{-1}.

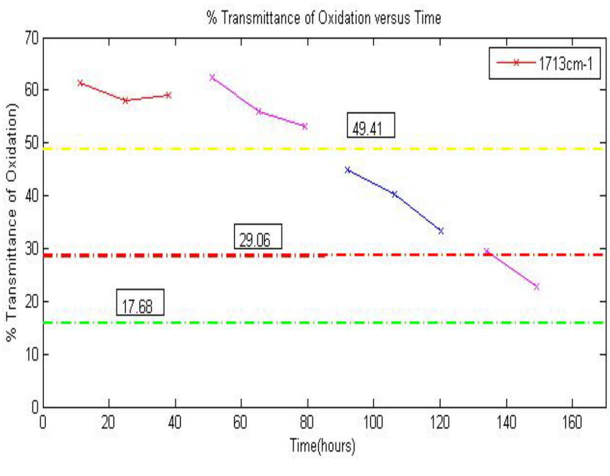

Fig. 9. Different percentages of degradation at 1050 cm^{-1}.

Based on the mathematical analysis, we may conclude that the lifetime of lubricant is directly proportional to the time. However, lubricant life expectancy also depends on how the driving style and engine's condition. Tables 2-4 show the comparison of different cases for the different type of band location. The negative value of time shows the lubricant of engine oil is starting to degrade and user should alert about their lubricant to avoid degrading engine performance. Furthermore, the negative sign also shows consumers use the lubricants exceed the life expectancy.

Table 2. Degradation Level at 70 %.

Prediction Time (Hours)	**Short trip driving with a new engine (degraded 70 %) (cm^{-1})**			
	1050	**1250**	**1713**	**1774**
T_{total}	439.6	574.3	496.7	1218.1
$T1_{new}$	428.5	563.2	485.6	1207.0
$T2_{new}$	188.3	288.0	299.0	876.0
$T3_{new}$	-80.8	62.9	140.9	663.1
$T4_{new}$	-319.6	-130.1	-19.6	476.0

Table 3. Degradation Level at 50 %.

Prediction Time (Hours)	**Average condition driving (degraded 50 %) (cm^{-1})**			
	1050	**1250**	**1713**	**1774**
T_{total}	308.0	379.7	370.2	952.9
$T1_{new}$	296.9	368.6	359.1	941.8
$T2_{new}$	113.0	165.5	206.9	668.8
$T3_{new}$	-85.2	-1.2	76.5	487.4
$T4_{new}$	-274.1	-164.3	-58.3	318.3

Table 4. Degradation Level at 15 %.

Prediction Time (Hours)	**Old engine with aggressive driving (degraded 15 %) (cm^{-1})**			
	1050	**1250**	**1713**	**1774**
T_{total}	72.8	31.0	143.9	479.1
$T1_{new}$	61.7	20.2	132.8	463.0
$T2_{new}$	-21.6	-54.1	42.3	294.0
$T3_{new}$	-93.1	-121.7	-38.5	214.4
$T4_{new}$	-206.6	-231.3	-127.5	102.3

In the worst case condition of oil usage which will be considered in low case of environment usage, it shows that the degradation due to chemical reactions in lubricant happened to band location 1050 cm^{-1}, 1250 cm^{-1} and 1713 cm^{-1}. For band location 1050 cm^{-1}, the lubricant starts to degrade on a slope 3 and 4 where the percentage of transmittance oxidation is around 45 %. The total time lubricants may use for this band location is around 439.65 hours. Besides that, for band location1250 cm^{-1} and 1713 cm^{-1}, the degradation of the lubricant is start degrade on slope 4 where the percentage of transmittance is around 40 % and 28 %, respectively. Based on the prediction analysis, the oxidation is not occurring in the band location of 1774 cm^{-1} for all of the cases. It is because E. Schwartz et al. [10] mentioned that the oxidation only occurred at the range band location of 1050 cm^{-1}-1250 cm^{-1} and 1700 cm^{-1} -1730 cm^{-1}. Then, the display was used to monitor the time usage of lubricant for giving the exact time to change the engine oil. In the normal case (50 %) the degradation is happening to band location 1050 cm^{-1}, 1250 cm^{-1} and 1713 cm^{-1}. The time usage for normal case is less than the low case environment used because the average wavelength was taken at 29.06 cm^{-1}. Base on the prediction, it shows that the degradation for band location 1050 cm^{-1} is occurring on a slope 3 and 4 and for band location 1250 cm^{-1} and 1713 cm^{-1} is occurring on a slope 4, respectively. The total time band location of 1050 cm^{-1}, 1250 cm^{-1}, 1713 cm^{-1} and 1774 cm^{-1} are 308.09 hours, 379.76 hours, 370.28 hours and 952.98 hours, respectively.

Besides that, for the aggressive driving style with the old engine condition, the oxidation will be degraded substantially and reduce the performance of their vehicles. The future life time for band location 1050 cm^{-1} is 72.8 hours. Then followed by band location 1250 cm^{-1}, 1713 cm^{-1}, 1774 cm^{-1} is 31 hours, 143.9 hours and 479.1 hours, respectively. The comparative use of different type of environment is easy the user to monitor the degradation of engine oil lubricants. The result of a life time is a warning limit only and user should alert about their current condition of engine oil. Therefore, the real time analysis of the engine oil condition is better than the mileage based for monitoring the lubricant condition.

5. Optical Sensor Measurement

To ensure the capability of optical sensor in monitoring the lubricant degradation, an experiment has been made on motorcycle engine oil for faster degradation results. Normally, motorcycle engine operates in double rotation per-minute (RPM) as compared to the car's operating condition. The data has been taken in different mileage as shown in Fig. 10 and an optical sensor has been designed using LED for different voltage determination. The differential value of voltage was stored in a Programmable Interface Controller (PIC) for displaying purposes as shown in Fig. 11.

Fig. 10. Sample Collection.

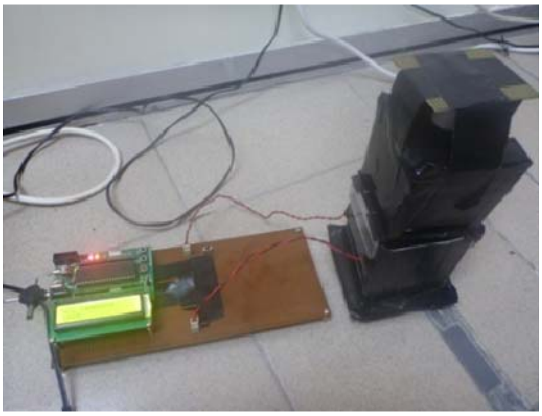

Fig. 11. Sensor with LCD Display.

In measurement process, the sample is placed on a transparent hole of 4 cm^2 and 0.5 cm height. White LED was placed on the top of the aluminum cover and the light passed through the sample and detected by LDR. The voltage drops due to the different kind of mileage were sensed by the LDR that placed at the bottom of the aluminum cover as shown in Fig. 12 below. This low cost sensor works manually and the samples of engine oil have to be placed alternately for different types of mileage. The reading of the voltage was taken at a 5 different engines to get the average value of voltage and then, statistical analysis was applied to see the degradation trend whether it is capable for the linear regression trend. The degradation trend of voltage in Fig. 13 shows that the voltage that received by the LDR decreased when the running mileage is increased. Therefore, we can say that this low cost optical sensor is capable to sense the different mileage condition of engine oil.

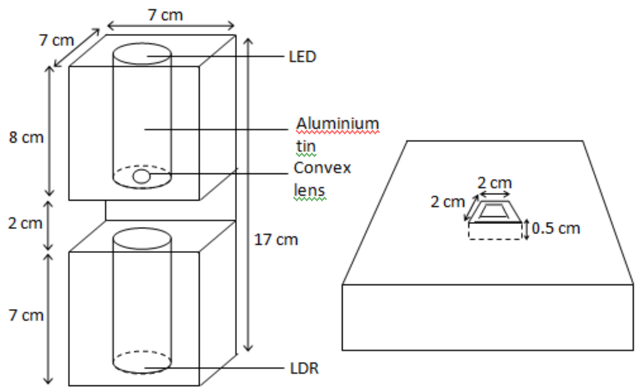

Fig. 12. Placement of Optical Sensor.

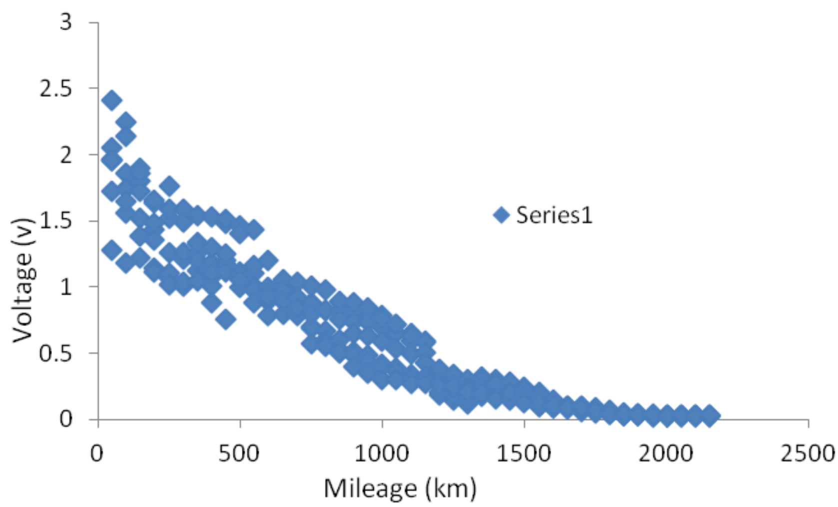

Fig. 13. Variations of Voltage Due to Mileage.

6. Conclusion

By using this algorithm and prediction analysis, it can be concluded that the real time analysis is better rather than mileage for monitoring the condition of the lubricant engine oil. For the future development, it is also recommended to study and investigate the others contamination such water, ethylene glycol, fuel, soot and wear metals that are causing the degradation of lubricant by using this technique. Also, a new aging technique must be developed by following the standard measurement in order to reduce the sample collection period because the more sample will give more precise results.

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Guide for Contributors

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- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
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