FPGA implementation of predictive degradation model for engine oil lifetime

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Abstract—This paper presents the implementation of linear regression model for degradation prediction on Register Transfer Logic (RTL) using QuartusII. A stationary model had been identified in the degradation trend for the engine oil in a vehicle in time series method. As for RTL implementation, the degradation model is written in Verilog HDL and the data input are taken at a certain time. Clock divider had been designed to support the timing sequence of input data. At every five data, a regression analysis is adapted for slope variation determination and prediction calculation. Here, only the negative value are taken as the consideration for the prediction purposes for less number of logic gate. Least Square Method is adapted to get the best linear model based on the mean values of time series data. The coded algorithm has been implemented on FPGA for validation purposes. The result shows the prediction time to change the engine oil.

Index Terms—Engine oil degradation sensing, FPGA, Online Monitoring

1. Introduction
An awareness of green environment and the need to reduce the yearly expenses, increase the requirement to have a new technique that can benefit the people to prolong their usage of engine oil and at the same time contribute to the green environment. There are a lot of parameters to be considered in determining the quality of engine oil. Viscosity, Total Acid Number (TAN), Total Base Number (TBN), oxidation and some of contamination including soot, water, glycol and other chemical contents are the type of parameters to determine the condition based on engine oil. Total Acid Number (TAN) and Total Base Number (TBN) also has been considered among the important parameter in term of quality indication due to the oxidation and the acidity content of the engine oil. The measurement method is based on the result of the carboxylic acids present after the oxidation process by using a titration method or optical spectroscopy [1]–[4].

Recent advances in optical technology have led to the more accurate in condition based monitoring. The parameters such as viscosity, oxidation, water and soot contamination can be monitored by exposed the sample into a certain optical wavelength. The optical wavelength can determine the type of material or acid contamination based on the light transmittance or absorbance. The degraded samples will reduce the percentage of light transmittance due to the increase of the absorbed light. At the receiver part, the amount of transmitted or absorbed light determined by the variation of voltage. From this optical signal, the warning limit of the used engine oil can be determined from the drastic decreased of transmittance percentage or gradual increased of absorbance [5], [6]. This technique can be implemented using Least Square Method (LSM) where the slope is monitored until it crosses the threshold value.

In recent years, efforts have been made to propose an online system to alert user the suitable time to change engine oil. But, the number of research which is focusing on online analysis technique is very few [7], [8]. Nevertheless the result of the research needs to be analysed according to the standard degradation parameters. In offline analysis, a deep knowledges about the lubricant
technology are required in making decision on engine oil replacement [9]. In order to have online system, statistical analysis is has been largely applied in different purposes; utilization of particle filtering algorithm as Remaining Useful Lifetime (RUL) prediction tool [10], web-based decision support system (DSS) in managing waste lube oils collection and recycling operations [11], predictive models in different techniques including Projection Pursuit Regression (PPR), Partial Least Square (PLS), Support Vector Machines (SVM), Linear Models, Generalized Linear Models (GLM) and Random Forest (RF) [1], partial least squares algorithm in development of calibration, prediction and validation models [12] and predictive maintenance algorithm including classification analysis, factor analysis, and multiple regression analysis [13].

In this paper, the implementation LSM in predicting the engine oil lifetime based on optical properties is presented. The work focuses on the monitoring technique of the degradation based on the slope variation. The slope variation is based on the oxidation wavelength of 1710cm⁻¹. The samples of engine oil SAE 10W40, 15W/40, CD-SE50 and SJ15W/40 (diesel) were used. Least Square Method were used as a method for prediction purposes which is coded using Quartus II software. Finally, the system design implemented on FPGA. The system is capable to predict the suitable time to change the engine oil and it relied to help the environment by reducing the amount of waste engine oils.

2. Experimental work

A) Sample collection and prediction algorithm

At this stage, the sample is collected for validation purposes of the developed prediction algorithm. CD-SE15W/40 is used as a first sample and second sample were taken from a type of CD-SE50 while the last sample is taken from SJ 15W/40. The samples have been analysed for oxidation effect to the optical properties where the virgin samples were oxidize in a temperature of 150°C. The oxidation process has been accelerated by the air pump and the copper wire catalyst. In this approach, the data resulted from FTIR analysis were extracted by using Perkin Elmer software by following the band location.

In this work, y-axis was denoted as percentage of transmittance %T while the x-axis denoted to running time (T). The main objective in this stage is to get the prediction time at x-axis for remaining oil condition, while the y-axis are the transmittance percentage (%T). The variation of %T are projected to the x-axis up to the warning and critical limit as shown in Figure 1.

![Figure 1 %T Projection and Engine Oil Lifetime Prediction](image)

Line $mn$ and $mp$ created from the regression technique using LSM consisted of 10 data. As an example, the current condition of %T at point b. So, the line is projected to the x-axis by using the value of slope obtained by the following formula;
\[
\hat{\beta}_i = \frac{SS_{x,y}}{SS_{y}}
\]  

\(y^*\) indicates half of \(\%T\) from the original value. \(mn\) is a slope from data point \(a\) to data point \(b\), whereas \(mp\) is the slope from data point \(b\) to data point \(c\). For example, the \(a-b\) line is projected to point \(y^*\) and the value of time is recorded as time \(x^*_2\). Thus, the remaining time to change the engine oil is determined by subtracting \(x^*_2\) from \(x_{n2}\) at point \(a\) and expressed as \(x_{pred}\). The \(b-c\) line also produced the predicted time of \(x_{pred}\) by subtracting \(x^*_1\) from \(x_{n1}\).

**B) System design and architecture**

This is the back end system design based the optical data input. The front end input is the optical sensor with the analog to digital converter. The back end system developments have been performed using Quartus II software environment where the algorithm is coded in Verilog language. The design is based on the LSM algorithm discussed in section 3.4.1. The LSM is the linear regression which is capable to be used as the prediction algorithm. The LSM is written in Verilog language to generate the Register Transfer Level (RTL) where the logic gates are generated. The system consists of clock divider, arithmetic and logic unit, register and input/output unit as shown in Figure 3.14. The system is composed of five blocks, namely, clock divider, data input processor, arithmetic unit, prediction and decision maker, and display unit. The input data is fed from Data in in 9-bit binary number representing the percentage of transmittance (\(\%T\)) in the \(y\)-axis, whereas the hours in the \(x\)-axis is taken from the Clock Divider input. The 9-bit as an n-bit data are chosen to be counted at the maximum number of 512 that represent the counting hours. Clock Divider is used to generate the 1 hour pulse because the data are sampled at every 1 hour and continuously sampled up to 512 hours due to the bit count of 9-bit. The maximum generating time is depending on the engine oil condition.

The engine oil degradation monitoring and engine oil lifetime prediction models discussed in sub-chapter 4.4 will be implemented in hardware. The main architecture of the system is shown in Figure 2. The system is composed of five blocks, namely, clock divider, data input processor, arithmetic unit, prediction and decision maker, and display unit. Clock Divider is used to generate the 1 hour pulse because the data are sampled at every 1 hour and continuously sampled up to 400 hour, depending on the engine oil condition. The input data is fed from Data in in 9-bit binary number representing the percentage of transmittance (\(\%T\)) in the \(y\)-axis, whereas the hours in the \(x\)-axis are taken from the Clock Divider input. The 9-bit numbers are chosen to be counted at the maximum number of 512 that represent the counting hours.

**Figure 2** The design block of the real-time degradation monitoring system

### 3. Result and Discussion

**A. Simulation Analysis using MATLAB**

This simulation is based on the collected sample as discussed in sub-chapter 4.2.3. The degradation
trend of optical transmittance for the three engine oil samples have been plotted in MATLAB as shown in Figure 4.10(a-b). Y-axis of the graph is referring to transmittance percentage (%T) while the x-axis is the running time (T).

In this work, the value of slope for the warning limit determined by the negative value of the slope. All three type of engine oil CD-SE50, CD-SE15W/40 and SJ 15W/40 which have been discussed in section 4.1.3 were analyzed using MATLAB for slope determination. As an example of the degradation trends for engine oil type CD-SE50 plotted in Figure 3(a), the warning condition occurred after the flat line because of the drastic drop of the transmittance percentage. At this time, the slope for this area will be calculated for lifetime prediction in the monitoring system. Figure 3(b) shows the regression data from the sample type of CD-SE50 from Figure 3(a). From here, we can see that the value of slope is determined between the time of 90 hours and 160 hours. At this time, the data are at the flat value at 85 to 90 hours before gradually decreased to the negative value.

![Figure 3(a) Degradation trends for engine oil type CD-SE50](image)

![Figure 3 (b) Regression data from the sample type of CD-SE50](image)

**B. Functional Simulation using Quartus II Software**

Slope is the main parameter in this development of monitoring system. It had been generated using LSM at every ten data. The first ten data were processed to get the value of the slope and stored in a Registers and named as `data_origin` as shown in Figure 4.29. The `data_origin` were taken from the first input data just after the engine oil was changed. It is also called as the virgin engine oil. This data will be used to compare the variation of degradation from the beginning of engine oil changes. According to the Figure 4, the origin data was 496 at ‘0’ hour. The first value of slope were obtained at t=9. This is the accumulated values of data from t=0 to t=9.
Figure 4 Accumulation of the first 10 data

The next slope will be obtained at \( t=10, 11, 12 \ldots n \) as shown in Figure 5. These value of slopes are used as the input to the system which contain of a 9-bit data.

Figure 5 Slope variation for sample set 1

C. FPGA Implementation for Data Validation

In this work, the data was taken based on the oxidation wavelength and the prediction monitoring are based on the slope variation. LSM is used as an prediction algorithm and implemented on hardware as an online monitoring system by using Altera DE2-115 development board as shown in Figure 6.
Figure 6  Hardware implementation setup using Altera DE2-115 development board

The data from engine oil type CD-SE50 have been verified using DE-2 board. It has been found that the warning limit occurred at 52 hours as shown in Figure 7. Here, the remaining engine lifetime started at 21 hours and decreased until critical condition. The critical condition reached at 141 hours as shown in Figure 8. At this stage, we can see that the predicted lifetime decreased until 0.

Figure 7  Warning Limit set 2 (CD-SE50)

Figure 8  Critical Limit set 2 (CD-SE50)

The degradation monitoring based on the variation of slope was supported by several research which was stated that the warning limit of the engine oil occurred when there was a drastic drop of light transmittance [14]. These approaches has been implemented in a hardware where the condition limit
will be displayed on LCD [5]. However, it was reported that the changes of optical data do not correlate well with actual oil degradation process [15]. The data was taken based on the variation of color which has no relation to the condition based parameter. In fact, the decision of engine oil changes are based on the offline analysis which is not suitable for online monitoring purposes.

Table 1 summarised the result of the condition based online monitoring system in Altera Board DE-2.

| Sample | Engine oil type | Warning limit | Prediction | Critical limit |
|--------|-----------------|---------------|------------|---------------|
| 1      | CD-SE15W/40     | 84            | 54         | 136           |
| 2      | CD-SE50         | 52            | 21         | 141           |
| 3      | SJ 15W/40       | 52            | 22         | 114           |

From Table 4.10, it can be seen that, the sample 2 have the longest usage of engine oil because of the critical limit at 141 hours as compared to the sample 1 and sample 3 which the critical limit occurred at 136 hours and 114 hours respectively. For the overall functional test, the sample 1 gave the better result in term of the warning and prediction limit. The warning limit for sample occurred at 84 hours while the prediction shows the remaining 54 hours respectively. The degradation trend of this sample is more linear than the others.

4. Conclusion

The monitoring and prediction system was built based on the LSM. The LSM consisted of the combinational logic gate from adder, subtractor, multiplier and divider. Then, it have been combined with another sub-system including serial shift register, membership function, condition monitoring and lifetime prediction. The functional simulation have been tested in Quartus software and then implemented on FPGA for real hardware implementation. The result shows that the usage for engine oil in time based slope monitoring achieved the objective to prolong the usage of engine oil for more than 100 hours. The LSM was designed with the combination of other system and implemented in FPGA for hardware design. As a result, a user will have a system that will give alert about the exact time to change their engine oil based on the real parameter such as TAN, TBN, viscosity and oxidation rather than mileage based with the Fuzzy based decision making of time to change the engine oil. Hence, the second objective of this work is achieved successfully. A significant portion of the work presented in this thesis have been devoted to the complete implementation of the system on FPGA. The actual data have been used to validate the capability of the overall system in monitoring and predicting the condition of engine oil. This is to fulfill the third objective of this work.

5. Acknowledgement

Appreciation to the Universiti Teknologi MARA (UiTM) that provide the academic research training and also Ministry of education for supporting this research through Research Grant Lestari [File No: 600-RMI/DANA 5/3/LESTARI (45/2015)].
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