Active Lubricant Condition Monitoring

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ABSTRACT

Lubrication in a mechanical system is like blood flowing through a human body. It is a great source to detect in advance any troubles in the system. As blood analysis shows the diseases in our body in a machine the oil analysis shows the fault in a system. Active lubricant condition monitoring is a great prediction technique which would help improve the reliability and reduce the maintenance costs for a system. The paper discusses about how to develop an Active oil condition monitoring where oil condition can be monitored online and how to achieve an active maintenance action. It discusses the design and setup of an oil condition monitoring system on a test bench provided. Different oil degradation parameters are analysed and sensors are introduced to monitor this parameters. Integration of microcontroller for wireless communication and use of different software's to acquire and process the data from the sensors to provide the real time condition of the system is discussed. This includes different actuation system that can be introduced to help the maintenance of the system to minimum and reduce the maintenance or damaging of the system components.

Keywords: Active Condition Monitoring System, Lubricant Monitoring, Oil Degradation, Online Oil Debris Analysis, Maintenance engineering technologies and integrated systems

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1. INTRODUCTION

Condition monitoring is the process of monitoring or determining the condition of different parameters of a machinery while it is running. It is a part of preventive maintenance technique which enables to do maintenance of the faulty elements and prevent any unwanted failures. This kind of maintenance technique ensures the operation of the machine is going smoothly and efficiently for a long period of time thus creating a more reliable system.

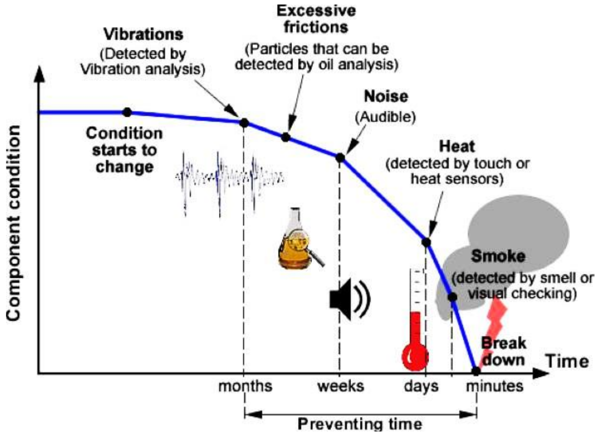

Figure 1 Development of a mechanical failure [20].

There are different kinds of condition monitoring techniques applied in industrial sectors. Some of the main techniques are: Vibration analysis, Lubricant Analysis, and Acoustic emission. Vibration analysis is a key component in condition monitoring. It is most commonly used in detecting faults in moving elements in a machinery such as motors, bearings and gears etc. [1]. It can detect any misalignment, unbalance and resonance due to a damage in a machine. Vibration frequencies from each component are displayed in Fast Fourier Transform spectrum. Each faults generate unique vibration frequency patterns which can be used to identify the faults. Different types of sensors are used for analysis depending on the vibration frequency e.g. accelerometers for high frequency, position transducers for low frequency [2].

Acoustic emission technique is a new technique in the field of condition monitoring. It uses high frequencies of the transient elastic waves generated by rapid release of energy from a localised point from a material. Acoustic emission occurs at a frequency range of 1kHz to 2MHz or greater [3]. The elastic waves are picked up using AE sensors, converted into electric signals and amplified using a pre amplifier to produce a time waveform spectrum. Ultrasound transducers can be used to pick up AE signals.

Timely lubrication is one of the essential process required for the smooth running of any mechanical system. Any moving parts in a mechanical system is lubricated to reduce friction between the moving elements. This will reduce vibration, acoustic disturbances, wear and tear of the system. The system needs to be actively lubricated to achieve this. The maintenance frequency of the system can be significantly reduced by introducing a technique to monitor the lubrication fluid regularly and from the analysis of this fluid the fault with the system can be deduced [4]. The temperature, quantity level, vibration and the debris within the lubrication fluid can be monitored and examined regularly using different type of sensors and the problems can be determined by the information provided by the sensor [5]. This type of condition monitoring system is much useful in equipment or machineries that are not accessible easily for maintenance or of high maintenance cost. E.g. offshore wind turbines, hydroelectric generators.

Active Lubricant condition monitoring is a significant means to ensure a proactive maintenance for an equipment [6]. It is a method to ensure the lubricant is in its acceptable level and condition to meet its function but to obtain information on the condition of the equipment. It also deduce any unwanted failures, anticipate any problems thus avoiding an expensive maintenance and extend the lifetime of the equipment [6] [7]. Lubricant also has its own life time; various factors contributes to lubricant fluid degradation. High temperature, oxidation, water content, foaming and debris accumulation are some of the reason for lubricant degradation. Monitoring some of the common parameters can give the sufficient data about the lubricant condition and about the equipment. Oil degradation is the term used to describe deterioration of physical and chemical properties of the lubrication oil while it is in service. It can affect the fluid performance and diminish the service life of the oil. This can also lead to the failure of major mechanical systems, making it more susceptible to maintenance works and less reliable. Understanding the mechanisms of oil degradation and methods to rectify it can help to increase the service life of the machine. The main factors affecting oil degradation are Oxidation, water contamination, aeration, thermal degradation and wear debris particles [8]. Understanding this factors and their root cause can be used to develop a sensor-based system that can monitor the running condition of the machinery and maintain it proactively. Different sensors can gain information on this factors and the information can be processed using advanced software to relate with observed results to provide the condition of the lubricant and equipment [4]. This can provide a time frame for the required maintenance and measures can be taken to prevent any maintenance.

Oxidation is one of the main cause of oil degradation. A chemical reaction can alter the composition of the oil over time. It is result of exposure of the oil with oxygen under high temperature. Even though additives are added to prevent oxidation, it can be depleted due to high temperature. Oxidation of the oil is the main cause of problems such as viscosity increase, rust formation and corrosion of metal components in machines [9].

Lubrication oil has small percent of air present in it. It can be in form of dissolved air, free air or as foam. These forms of air presence in the can create air bubbles in the circulating oil. The dissolved air under high temperature can cause oxidation of the oil. Air bubbles can create cavitation within the metal components

[10]. It can also cause component wear due to reduced lubricant viscosity [11].

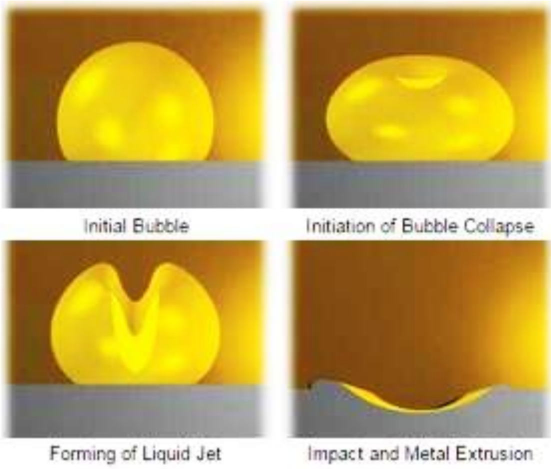

Figure 2 Cavitation in metal due to air bubbles [11].

Water presence in oil can also cause oil degradation. Water can find its path into machine parts and be dissolved or suspended in oil. This can lead to increased depletion of additives in oil and hence causing oxidation. Water content in oil can be exposed to parts in motion and cause hydrogen embroilment that in turn reduces fatigue life of metal parts. Excessive wear can occur in rotating parts because of loss of the hydrodynamic oil film due to the incompressibility of water compared to oil. For e.g. life of a journal bearing can be reduced as much as 90% as result of water content as little as 1%.

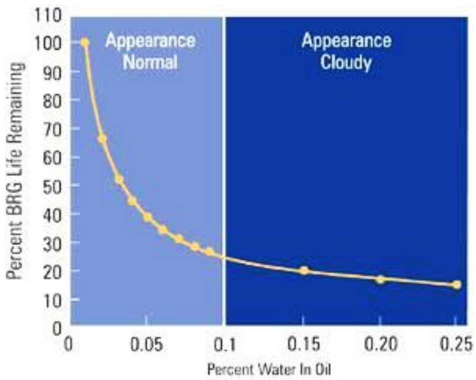

Figure 3 Graph showing relation between life of a bearing and water percent in oil [18]

Thermal degradation is the term used to describe oil degradation due to high temperature. Temperature can affect the characteristics of the oil significantly. High temperature can cause oxidation and change the viscosity of the oil. Low temperature can affect the pour point of the oil. These can change the flow of the oil resulting in insufficient lubrication of the components and damage to the components.

Wear or Debris particles of microscale can get accumulated in the oil and change the oil characteristics. Debris accumulation can occur when wear particles are washed down by the oil from machine parts. This debris when come into contact between any parts in motion can cause further wear and thus creating a path for failure of the part. Wear can be caused due to different reasons. Material removal on a surface of an object depends upon the load acting on it, composition of the surface and nature of the stress-inducing load and the environmental conditions. Understanding different types of wear and nature of it can help to identify the problem within a working machine. Generally, wear modes can be classified into three types

1. Surface to Surface wear
2. Fluid to surface wear

3. Environmental to surface wear

Understanding different types of wear and nature of it can help to identify the problem within a working machine [19].

Rubbing (Break in) (Abrasive Wear), figure 4 (d), is the most common type of wear. This type of wear occurs in an equipment when a sliding element rubs with a stator surface or in between two sliding elements. This results in the formation of low wearing surface with particles of benign nature in the form of platelets. Wear debris are mostly found in the lubricants during machining

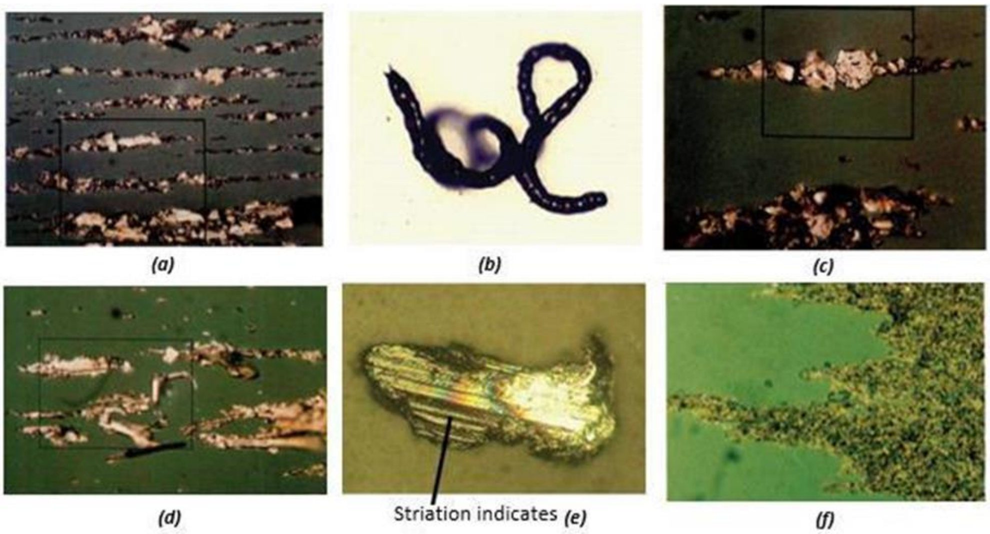

Figure 4 a) Rolling and sliding wear debris (b) Cutting wear debris (c) Rolling wear debris (d) Rubbing wear debris (e) Sliding wear debris (f) Chemical/corrosive wear debris

Cutting Wear (Abrasive Wear), figure 4(b), is produced when two surface penetrates with each other. The debris is formed when one surface is gouging over the other resulting in long ribbon like pieces. eg: Machining swarf on a lathe. Rolling Wear (Surface Fatigue), figure 4(c), produces fatigue on the surface and found in the components of rolling motion contact. Debris formed in the wear are in spherical or laminar shape. eg: Rolling motion contact in ball bearings. Sliding wear, figure 4(e), occurs due to the impact of load and speed between the contacting surfaces. The contacting surfaces breakaway small to large particles. As the load and speed between the contacting surfaces increases, size of the debris and wear rate increases. Rolling and Sliding combined wear, figure 4(a) is caused by the combined action of fatigue and scuffing. This wear is commonly found in gear system, particularly in the gear line (between two gears). The combination of sliding and rolling produce a complex fusion of the debris in between the gears (contact surfaces). Chemical/Corrosive wear, figure 4(f) is caused by fluid properties or heavy contamination from water, acid, bacteria or acid, which results in the formation small particles. In addition to this impurity from the environment also influence in this type wear. To tackle this type of wear lubricants are added with additives.eg: ferrous oxide particles formed due to the reaction between oxygen and iron.

2. DEVELOPMENT OF OIL CONDITION MONITORING TEST BENCH

The test bench for the project was assemble and provided by the University. The test bench is by the size of 1m to 0.7m size. It includes of an oil circulation system consisting of oil tank, PVC pipes, different sensors, centrifugal pump and filter. The test bench is updated with different sensors to monitor the oil condition, temperature, humidity, Viscosity, wear and Debris particles. The actuator system is also updated to respond to any undesirable condition by installing a 3-way valve that can change the flow of to the machine to avoid any further damage.

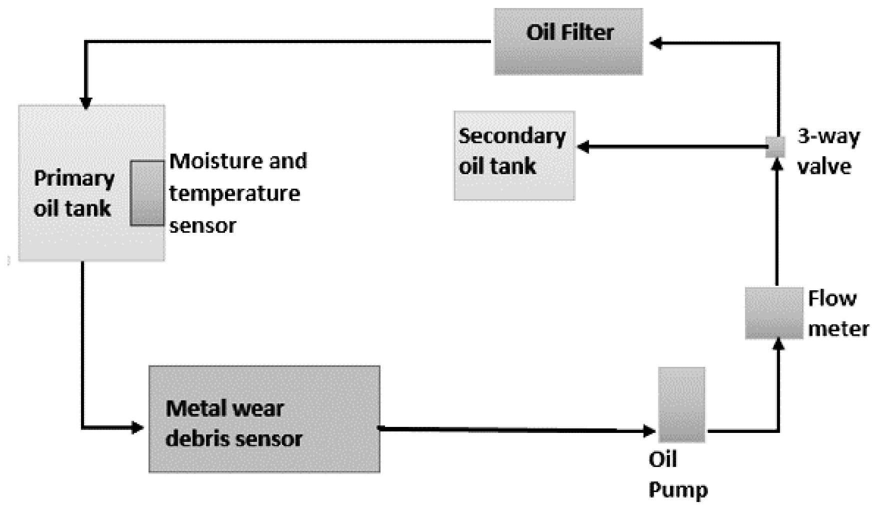

Figure 5. Block Diagram for test bench design.

The oil is stored in the tank and flows through the PVC pipe for lubrication as required. The PVC pipe is connected to a Metallic wear debris sensor and a flow rate sensor. The Debris sensor assess the contaminant particles in the oil and the flow rate sensor checks the flow rate of the oil passing through the sensor. The oil is then streamed into a 3-way valve which determines flow of the oil according to the debris data from the Debris sensor. The 3-way valve is used to change the direction of oil flow to a different tank if oil contamination or degradation is higher than the acceptable value. If the contamination or degradation of oil is on acceptable levels, the oil direction is not changed and it is filtered using a filter system. The filtered oil then flows back to the tank where the temperature and moisture sensors are placed and assess the oil condition. The sensors are interfaced with the LabVIEW software using a wireless microcontroller. The microcontroller system is used for data acquisition and actuation signal output. A wireless communication is setup over Wi-Fi with the PC.

A 10 litre stainless steel fryer is used as the oil tank in the test bench. It also includes a heater that can be used to heat up the oil to a temperature of 120ºC. Two different openings are placed on the oil tank where the PVC pipes for the oil to flow out and Flow in are connected.

PVC pipes was used for piping of the system. PVC pipes are lightweight, flexible and has a main advantage on application of joint tightness. It is flame resistant to temperature 450ºC. Its elastic properties reduces the magnitude of pressure surges. The pipe has a diameter of 15mm and has different fittings including angle, male and female fittings with O – ring oil seal to avoid any oil leakages due to pressure.

Filters used are a stainless steel cleanable with magnetic filter element to collect debris of microscopic range. In order to increase filter corrosion resistance, the filter surface has been anodized with bright dip blue finish. The filter is supported by an O- ring.

3-way valve is a 3 Port BSP ⅟ **2** DN15 Brass valve by BACOENG. It is an electrical valve that can change the direction of the flow of oil from main valve to secondary valve. A PWM signal from a microcontroller can be used to achieve this.

3. DESIGN AND DESIGN AND DEVELOPMENT OF AN ACTIVE LUBRICANT CONDITION MONITORING SYSTEM

For effective lubricant condition monitoring, a low cost sensor system needs to be developed to monitor different oil degradation elements. The system is to be designed to identify the faulty component and property of damage depending on debris size and characteristics.

Viscosity of a liquid can be explained as a quantity used to describe as fluids resistance to flow. It is an important property of a lubrication fluid. Oil has lower viscosity than water as it less dense that is oil have less resistance to flow than water. Change in viscosity of lubrication fluid can be due to oil degradation. Oil degradation can increase or decrease viscosity of the lubrication. Increase in viscosity can caused due to oxidation or due to contamination in oil. High viscosity can restrict the flow of oil to components and reduce the ability to lubricate. Decrease in viscosity of oil can cause weakening of the oil and will not be able to prevent contacts between metals. Monitoring the viscosity of the Lubricating oil can provide us information about oil degradation and condition of the equipment. Comparing the data acquired to the known parameters can help to identify the problems. Viscosity of a fluid can be calculated using the Poiseuille's Law [12].

$$Q = \frac{\pi \mathrm{P} r^4}{8\eta l} \qquad \textit{Equation 1}$$

Where;
Q is the Flow rate
P is the change in pressure in the valve r is the radius of the valve
η is the Viscosity
l is the length of the valve

In the test bench provided a flow meter is installed to acquire the flow rate of the oil and an oil pump is used to circulate the oil around the system. The pump provides a pressure of 0.8bar which is 80kPa. The radius of the piping is 7.5 mm and the length is the distance between the pump and the flow meter. Using these values, the Viscosity of the oil can be determined.
Flow meter used is a flow rate sensor that measures the flow of oil through the system. It has a rotor, Hall Effect sensor and PCB electronics. The flow of oil can be measured by connecting it to the micro controller. The microcontroller outputs the flow measurement by counting the pulse rate of signal output from the flow meter. It works up to temperature condition of 80^{o}C.

The centrifugal pump used to circulate the oil is a Merry Tools Mini- type pipe pump. It is a 90W 0.8 bar electronic water pump booster. It has a stainless steel motor housing, brass impeller and copper wires. The pump can be activated by switching on manually. The pump can be used to for a liquid temperature of up to 80^{o}C at a max flow rate of 18L/Min.

A metallic wear Debris sensor is used to determine the size and quantity of the wear and debris particles present in the oil. Parker kittiwake On-line metallic wear debris sensor provides real time wear debris count for both ferrous and nonferrous wear metals. It uses magnetometry combined with smart algorithms to provide a particle size speculation and count. It can detect ferrous materials of size greater than 40 micron and non-ferrous particle of greater than 135 micron. It can quantify the metallic composition size category and particle count of the debris in oil. It operates on a temperature of -20^{o}C to 70^{o}C [13]. The sensor has a fluid flow range of 0.3 – 1.9ms^{-1}. The minimum flow rate and maximum flow rate required for the sensor can be thus calculated.

$$\text{Flow rate } Q = V.A$$

Where V is the volume of fluid and A is the cross sectional area of the pipe =A=πr^2

$$\text{Min Flow rate } Q = V.A$$

$$= 0.3\ \pi\ 0.0075^2$$

$$Q = 0.000053 m^3/s = 3.18 litres/min$$

$$\text{Max flow rate } Q = V.A$$

$$= 1.9\ \pi\ 0.0075^2$$

$$Q = 0.00035 m^3/s = 21 litre/min$$

The pump provides a maximum flow rate of 18L/Min which falls within the range of sensor. The sensor is capable of detecting Ferrous and non-ferrous particles. It can also measure the size of the particles. It works on a balanced coil, full loop system. Three equally spaced coils are wrapped around an aperture. The transmitter coil in the centre creates an electromagnetic field. When the debris pass through aperture there is a disturbance in the magnetic field strength and the disturbance is picked up by the receiver coils and analysed by controlled electronics. Detection occurs if the sensitivity threshold is exceeded.

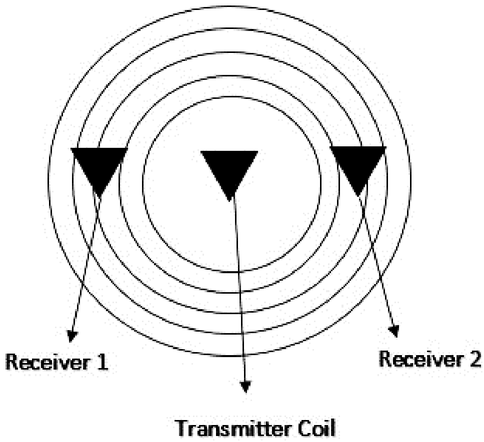

Figure 6 Schematic diagram for aperture of Wear debris sensor

The sensor assumes the debris spherical and calculates its volume using its dimensions. The spherical debris diameter is used to calculate the comparative volume of wear debris and pinpoint the origin of debris. A NTC temperature sensor was used to detect the temperature variations in the tank. The sensor has a temperature range of -40°C to 120°C. The thermocouple is used as resistor in a voltage divider circuit. So as the thermocouple value changes the output voltage changes. 10k ohm resistor is used as the thermocouple has a resistance of 20k ohm. To calculate the amount of water content in the oil a soil moisture sensor controller module was used. It senses the humidity in the environment. It has a potentiometer to adjust the sensitivity and is used to produce a warning if the water content in oil rises certain level.

NI LabVIEW is a development environment with a graphical programming syntax to create and code engineering systems. LabVIEW is integrated with a wireless Atmel microcontroller system to acquire the measurements from the sensor. Measurements are analysed in LabVIEW and control system can be developed for the automation of the system. Modbus is a communication protocol developed to be used with Programmable logic controllers. It is a communication protocol designed to transmit data between electronics devices. Modbus has both TCP/IP and serial Communication to transfer data [21]. Modbus TCP/IP uses TCP interface running on Ethernet. The MWDS uses Modbus communication to transfer the data to PC. The Modbus Register Map for the MWDS can be accessed by developing a program in LabVIEW.

The system can be programmed to send a notification to the Engineer in case of a failure. It can be designed to send a notification email from LabVIEW using the SMTP email function. The user email information can be configured by entering the senders email address and outgoing mail server. DebriSCAN is a software that can be used to acquire the data from MWDS. The software provides the different characteristics data of the debris in oil and gives feedback and alert whether the system is under normal running condition or abnormal running condition.

The Atmel microcontroller (IDE) is a software used to write the Atmel microcontroller programs and upload them into the Atmel Board. The Atmel IDE has example program for each board which is helpful to write the program for the system. It can be programmed to read the sensor data and display it in serial monitor. Using Atmel microcontroller the Uploading the program and displaying the data in serial monitor can be done wirelessly using Atmel IDE.

Open SSH is an application available in the android operating system that allows to connect to the Atmel microcontroller using Secure Shell network protocol. The SSH protocol allows to connect to a server securely through an unsecured network. The Open SSH reads the data send by the Atmel and displays it in the remote device like a serial monitor.

An intelligent system needs to be developed for the system adapt to the different environmental or machine condition e.g. heating or cooling of oil, provide or more less lubrication and communication with another unit and compare the system condition. Intelligent system can be defined as an embedded, internet connected computer machine that is capable of acquiring, analysing data and communication with other systems. An intelligent system should include security, connectivity, remote monitoring and management capacity and be able adapt according to the acquired data [16]. For the system to respond to a data a logical system needs to be integrated into its programming. Fuzzy logic is a logical system that can be used for fusion of different sensory measurements and create a decision making algorithm. Fuzzy logic uses the degrees of truth instead of the usual Boolean logic of true or false. It helps to give a value to the true or false using various states in between. Fuzzy logic is helpful in development of an artificial intelligence in the software that can conclude to a human like decision based on collective data from the system.

4. ACTIVE CONDITION MONITORING SYSTEM VALIDATION

The different sensors placed in the test rig was connected to the Atmel microcontroller. The code was developed in LabVIEW to acquire the signal and visual warning aids were designed to ensure the system is on normal operation limits. Preliminary testing for the sensors was done and the results was observed. The data from the temperature sensor displayed in LabVIEW using graphics. The sensor was tested at room temperature.

The LEDs was used as visual warning system for the user. It High temperature lights up if the temperature exceeds 80 degrees and low temperature led if temperature falls below 10 degrees Celsius. The moisture sensor data was acquired and displayed in LabVIEW. The sensor was tested in different conditions. It was immersed in oil, mixture of oil and water, and just water. In oil the value was above 1000 which shows dry condition and in water the value was less than 820. Unfortunately, the mixture of oil and water reading was not reliable as water droplets was covered with thin film of oil which produced a dry condition result. Significant amount of water has to be added for the sensor to show a moisture presence in oil. The oil pump was turned on and acquired the flowmeter data. The code was developed to count the pulse output from sensor. The Pulse frequency and the flowrate was calculated from the pulse count and displayed. Low flow rate limit set for 3.2litres/min and high flowrate was set for 21 litres/min. The wear debris sensor data was displayed in LabVIEW software when wear and debris particles was introduced to the oil. The MWDS was able to detect the particles and categories it into size and ferrous or non-ferrous class.

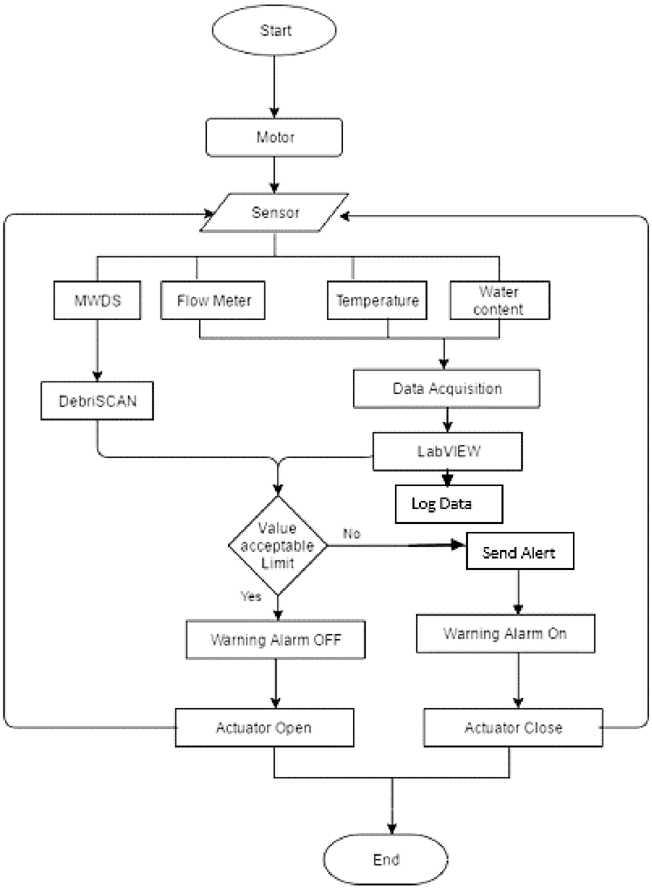

Figure 7 Flow Chart Diagram for ALCM system

The complete Active Lubricant Condition Monitoring system is a sensory actuation system controlled by an embedded system and software developed in LabVIEW. The system is developed as a machine health monitoring system which can predict the failure and the current condition of the system based on the oil degradation parameters. The system monitors the sensor inputs and activate the actuation system based on this data. The wear debris sensor detects the wear particles flowing through the system and the data is displayed in the LabVIEW interface in the relevant section. A warning limit and alarm limit can be set for maximum particles per minute and maximum mass for particles per hour can be set. When the limit is reached the system activates the actuation system and changes the direction of the flow of oil from primary tank to the secondary tank using the 3 way valve. Once the particle count per minute or mass per hour values goes down below the set limit, the system activates the actuation system changing the flow of oil into primary tank to default operation. The control of the actuation system is automated based on the system condition. It can also be manually controlled using a flip button in case any malfunction to occur and control of the actuation system is required.

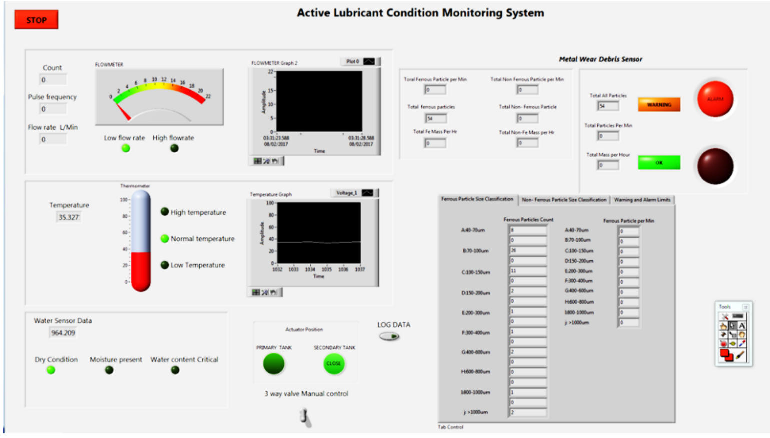

Figure 8. Active Lubricant Condition Monitoring system in LabVIEW

The wireless Active condition monitoring system was developed using Atmel IDE. Sensors was connected to Atmel microcontroller board. The Yun microcontroller board can be connected to the PC using Wi-Fi connectivity. This allows the microcontroller to send and receive the sensory actuation system data wirelessly.

The 3 way electric valve was able to be controlled wirelessly through Atmel microcontroller and Notification for is displayed on the serial monitor when the valve opens or closes.

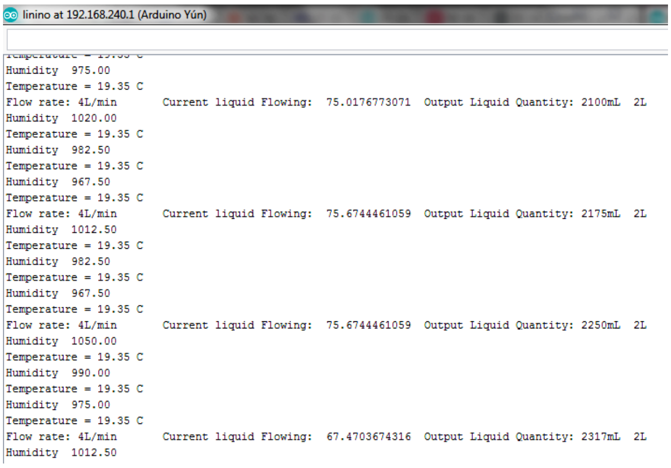

Figure 9 ALCM system data displayed in PC wirelessly

The Wireless ALCM system can be accessed wirelessly through any PC, Smart phone or tablet as long as it has Wi-Fi connection to connect to Atmel microcontroller and Serial program or SSH application available in the device. The actuator can also be controlled through this device as same as the PC to close or open the 3 way valve. Security of the system was considered. The system is also secured using password. The system can only be accessed through SSH client application in smart devices. SSH is a Secure Protocol used primarily as means to connect remotely to Linux servers.

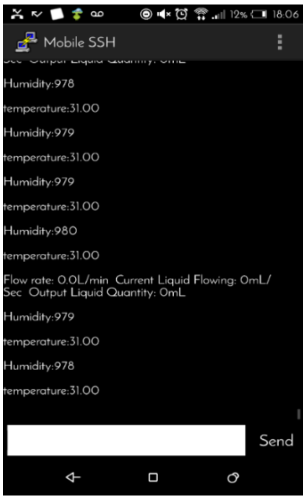

Figure 10 Mobile SSH client application with the shared data displayed on a smartphone (Android platform)

5. CONCLUSION

The ALCM Program was developed in LabVIEW software to monitor and control system in real time. The aim of the project was accomplished by monitoring the factors that causes oil degradation. MWDS, Temperature sensor, Water Content sensor, Flowmeter are the sensors used to monitor the oil conditions. The sensors were able to provide information regarding the oil degradation parameters such as particle count, classification, size of debris, water content, temperature and viscosity. The actuator system was designed using a 3- way valve, it was able to direct the flow of oil to a secondary tank when debris particle of set limit is detected in the system. This design feature was included to avoid any further damage to the system due to the degraded oil. The system was able to alert the user of system failure by sending an email. An ALCM program was also developed using Atmel microcontroller and software interface to monitor the system condition and control it wirelessly. The sensors were tested and a measurement was acquired but more research and testing has to be done to interpret the data and recognise significant characteristics machine condition so that; it can also provide a most likely scenario of failure where potential consequences and its probability of occurrence can be determined. Active real time monitoring of the system can provide any indication to potential failure and condition of the system.

6. FURTHER WORK

Fusion of measurement from these sensors using a fuzzy logic system can provide an information of condition of the machine to create an intelligent ALCM system. The system can be made more efficient elemental analysis is required to identify the failed components. Further testing of the system with different failure modes is required and develop the system to identify the root cause of the failure. Combine oil condition monitoring with other condition monitoring techniques such as vibration and acoustic emission monitoring to design an effective condition monitoring system. The Atmel controller has the functionality to connect to the internet which can be used to send and receive data through TCP/IP. This can help to create an ALCM system that can be accessed via online. Interfacing the Atmel microcontroller with LabVIEW to create a GUI which is easier for the user to interpret the Sensor data. Develop an intelligent Maintenance system with sensors and actuators were the Machine can predict the failure and use the actuators to rectify the failure or inhibit any further damage to the system. Develop an ALCM system that can communicate to other system, compare the data to self-assess the system performance and make it more efficient and reliable.

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