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Condition Monitoring of an Automobile IC Engine and Gearbox through Used Oil Analysis

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ABSTRACT
It is becoming very essential to regularly monitor different machinery to detect failure initiation and to prevent the failure by taking timely remedial action. The aim of this work is to present a systematic analysis of lubricant degradation of an IC engine and gearbox of an automobile. The automobile has been monitored over a period of five months through the oil analysis of lubricating oil. Two efficient techniques FTIR oil analysis using Fluid scan and viscosity testing using Viscotester have been performed to monitor oil condition. Later on, based on the oil condition, the probable condition of the engine and gear box is identified and the remedial actions which need to be taken are explained. Lastly, the significance of this method as a reliable condition monitoring tool in order to prevent the catastrophic failure of the machinery and expensive component replacement is illustrated.

Keywords: FTIR Oil Analysis, Lubricant, Degradation, Condition Monitoring, Catastrophic Failure.

1. Introduction

Condition monitoring technologies are being utilized widely for the purpose of diagnosis and alert in the cases of near or complete failure. Automotive engines are specific mechanical systems that are potentially exposed to failure and therefore require condition monitoring technologies to be used in order to detect those potential failures [1]. Engine is the main part of the automobile vehicle. Diesel and petrol engines can be used for the automobile vehicle. Performance of the engine is actually dependent on the good condition of the various engine parts i.e. piston, cylinder, connecting rod, cam shaft, etc. The failure of these engine parts can be reduced by following proper condition monitoring technique like oil-based condition monitoring [2]. Gearbox is also as important as engine in an automobile. Regular condition monitoring of automobile gearbox is also required in order to prevent the sudden breakdown of gearbox. There are a number of condition monitoring techniques, among which vibration-based monitoring, thermography, oil-based condition monitoring and nondestructive testing (NDT) are noteworthy. There are few techniques which can be used for oil analysis. However, each of the method can not fulfill all the requirements needed to attain clear idea about machinery health. Therefore, combining two or more techniques can be more reliable for fault diagnosis of the component as well as for the oil condition detection. In 2016, work has been done on reducing the failure of engine component using oil analysis. Using spectrophotometer different parameters of used oil like total acid number (TAN), viscosity, ash content, wear metal particles, etc. were measured [2]. In another work, oxidative degradation analysis of biodiesel blends was done using FTIR spectroscopy, Ultraviolet-visible spectroscopy, thermogravimetric analysis, etc. to perform oil condition monitoring [3]. Perkin Elmer Spectrum 400 FTIR spectrometer has been used in this work to perform FTIR oil analysis. Later on, in 2017, degradation rate of synthetic lubricating oil was analyzed and evaluated by exploiting electron paramagnetic resonance and infrared Fourier transform [4]. In 2017, analysis on the influence of filtrated biogas on oil contamination and degradation, as well as on engine wear was performed [5]. After analysis, trends of different parameters like viscosity, nitration, sulfates, etc. were observed. In 2017, diagnosis of various running distances for used oil samples was carried out to find the relationship between distance and level of depletion of physical properties of oil using Kittiwake oil testing equipment [6]. In 2019, work has been done on the analysis of engine oil samples of a fleet of urban buses [7]. After studying the evolution of degradation, a predictive maintenance policy for oil replacement was developed. Later on, again in 2019, a review was done on research trends and development of lubricant condition monitoring based approaches applied for maintenance decision support [8]. It was suggested that chemical additives, contamination and elemental compositions need to be tested for efficient monitoring.

This work presents the determination of lubricant contamination and condition by Fluid Scan (FTIR Oil Analyzer) and Viscotester. Automobile IC engine and gearbox have been monitored for five months

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approximately through used oil analysis. Gradual changes in the oil characteristic data were analyzed to get an idea about lubricant condition, as well as the component health. As Fluid Scan and Viscotester are very handy devices, they can be carried always, and on-site monitoring is possible.

2. Different Condition Monitoring Techniques

There are a number of condition monitoring techniques in the literature. Among them vibration-based monitoring, thermography, oil-based condition monitoring and nondestructive testing are significant.

2.1 Vibration Based Monitoring

Vibration analysis is the technique used a lot since the greatest population of the typical plant is mechanical. The technique uses noise or vibration created by mechanical equipment and in some cases, by plant systems to determine the actual condition of the plant. The technique is extremely reliable in detecting abnormal machine behavior. However, this method is expensive and requires a high level of expertise. Therefore, only the most critical equipment could justify the expense to implement this method [9].

2.2 Thermography

It monitors emission of infrared energy to identify the operating condition. By detecting thermal abnormalities, an experienced inspector can locate and define the problems within the plant. However, the temperature measurement using infrared methods is complicated as there are three sources of thermal energy that can be detected from the object i.e. energy emitted from the object itself, reflected from the object and transmitted by the object. Only emitted energy is important in condition monitoring and thus, other two sources must be filtered out from the acquired data [9].

2.3 Oil-Based Condition Monitoring

In this method, the in-service oil is tested to determine the oil contamination and degradation to determine overall oil condition, as well as the machinery condition. Wear debris analysis of the lubricant gives the detailed picture of the machinery condition and gives the root cause of wear. FTIR oil analysis, viscosity testing, etc. are used normally to determine oil contamination and degradation. Ferrography, SEM testing, etc. are generally used to monitor wear debris present in the lubricant. By wear debris analysis, the root cause of wear is known. Oil-based monitoring is quite significant as the gradual change in oil properties can be observed by sampling the oil after few working distances, and continuous change in the lubricant and condition of equipment can be monitored using this method.

2.4 Nondestructive Testing

Nondestructive testing are methods to evaluate material integrity for surface or internal flaws or metallurgical condition without interfering in any way with the destruction of the material or its suitability for service. This method provides a cost-effective means of testing of a sample for individual investigation and examination or may be applied on the whole material for checking in a production quality control system. Sometimes, it requires more than one method to detect the fault and thus, combination of methods is often necessary. Common methods of nondestructive testing are visual inspection, microscopy, radiography, dye penetrate, ultrasonic, magnetic particle, acoustic emission, etc. [10].

In this work, oil-based monitoring technique has been used to identify the condition of the automobile.

3. Methodology

Engine oil and gear oil of a regular moving truck were monitored for about five months. Few drops of engine oil and gear oil were collected repeatedly after certain distance traversed by the vehicle and gradual change in the condition was observed. The methodology is divided into three sections, which are discussed below.

3.1 Sample Collection

Four engine oil samples including fresh oil and six gear oil samples including fresh oil were collected over five months. Samples were taken at an interval of 2000 km approximately of the traversed distance. However, as the lifetime of gear oil is generally much higher compared to the engine oil, that’s why first sample of gear oil has been taken after 10000 km approximately of the vehicle running and then remaining samples were taken at an interval of 2000 km. Cleaned cylindrical jars of about 5 inch diameters were used to collect the samples. Jars were placed under the drain port of the sump. By opening the port, the samples were collected.

3.2 FTIR Oil Analysis

Fluid Scan 1000 has been used to perform oil condition analysis. Different parameters like bubbles, free water, total acid number (TAN), oxidation, water content were measured and their variation with time and distance traversed were observed. The properties oxidation, TAN and water content correlate to the different ASTM protocols [11]. When fresh oil samples were inserted, fluid scan automatically detected the type of oil and displayed the benchmarks for that particular type of oil. Benchmarks of different parameters of engine and gear oils have been shown in Table 1 and Table 2, respectively. Only a few drops of oil were required to run the tests. The device instantaneously showed the result once each sample was inserted.

3.3 Viscosity Analysis

Viscosity is a significant property of oil, and must be considered in oil analysis. The correct balance between high viscosity for load carrying and low viscosity for ease of circulation must be considered for any lubricant [12]. Spectro Visc Q3000 was used to determine the viscosities (at 40°C) of the gear oil and engine oil samples. About 60µl of each sample was loaded on the top and due to gravity, the sample fell into the device. This device then used three sensors to determine the viscosity. Lastly, variation of viscosities was observed.

4. Results and Discussion

4.1 Contamination Analysis by Fluid Scan

Oil degradation and contamination were analyzed using fluid scan. The analyzed values were then compared with the benchmarks, as shown in Table 1 and Table 2. For ease of understanding, engine oil samples taken at 0 km (fresh oil), 2000 km, 4000 km and 6000 km are expressed as samples 1, 2, 3 and 4, respectively. On the other hand, gear oil samples taken at 0 km (fresh oil), 10000 km, 12000 km, 14000 km, 16000 km and 18000 km are expressed as samples 1, 2, 3, 4, 5 and 6, respectively. Different properties like air bubbles, free water, water content, oxidation and total acid number were measured by Fluid scan.

Air bubble is one of the most important parameters of lubricant which needs to be checked during oil analysis. Air bubbles in lubricant can cause foaming, which ultimately leads to oxidation of oil, cavitation of components and in extreme case, it leads to failure of different components [13]. The presence of bubbles in engine and gear oil samples are illustrated in Table 3 and Table 4, respectively. As seen from tables, both engine and gear oil samples have negligible amount of bubbles in first samples and no bubble in rest of the samples. Therefore, the results are satisfactory.

After analyzing bubble content, free water contents of both oil samples were observed. In oil, water can exist in three states. They are dissolved water, emulsified water and free water. Among them free and emulsified water are most harmful. Dissolved water is less harmful compared to them [14]. Water in oil can result in the viscosity change and cause additive depletion and leads to formation of sludge, varnish, etc. [12]. Beside this, under certain load condition free water breaks into its constituents i.e. hydrogen and oxygen. The free hydrogen ion then results into hydrogen embrittlement. Again, this water can play direct role in aging rate of lubricant. Presence of water increases oxidation of oil results in premature aging of oil. In addition, certain types of synthetic oil also react with water which is noteworthy [14]. Table 5 and Table 6 show free water contents of different samples of engine and gear oil, respectively. In case of engine oil, it has been observed that significant amount of water is present in third and fourth sample which is very alarming. Therefore, immediate change in lubricant is required for engine oil. Inspection should be done for coolant leakage, non-water tight seals i.e. cylinder head gasket and lastly, the engine crack as they are the prime reasons for water mixing with the engine oil. Exact condition of the seals will be known when these parts will be observed. On the other hand, no significant free water is detected in gear oil samples. All the gear oil samples had free water content of 0.01 abs/mm^2 which is negligible. Therefore, no preventive measure is needed regarding free water content.

Dissolved water can also be taken into consideration during oil condition monitoring as every bit of water is responsible for gradual damaging of the machinery component. Trends of dissolved water content for engine oil and gear oil during the observed distance period are illustrated in Figure 1 and Figure 2, respectively. From the figure, it is observed that all samples of engine oil have the water content which is below the upper permissible range and increased with the increase of distance traversed. As the water content is in permissible range therefore no extra caution is necessary regarding this parameter. Also, in case of gear oil, it has been observed that the water content is in permissible range and gradually increased over distance. However, the curve became steeper gradually over distance. Therefore, it should be checked whether there is leakage or not between automatic transmission fluid (ATF) and the coolant in the radiator as the same coolant that cools the engine also cools the transmission system. If there is leakage then measures

Table 1 Benchmark for Engine Oil (Castrol)

Property	Low	High	Unit
Bubbles	1.00	N/A	Bubbles
Free Water	N/A	0.30	abs/mm^2
Oxidation	N/A	70.00	abs/mm^2
TAN	N/A	3.50	mgKOH/g
Water	N/A	500.00	ppm

Table 2 Benchmark for gear oil (gear splash)

Property	Low	High	Unit
Bubbles	1.00	N/A	Bubbles
Free Water	N/A	0.30	abs/mm^2
Oxidation	N/A	25.00	abs/mm^2
TAN	N/A	3.50	mgKOH/g
Water	N/A	600.00	ppm

Table 3 Bubble contents of engine oil samples

Sample Numbers	1	2	3	4
Bubbles (Bubbles)	1.30	0	0	0

Table 4 Bubble contents of gear oil samples

Sample Numbers	1	2	3	4	5	6
Bubbles (Bubbles)	1.30	0	0	0	0	0

Table 5 Free water contents of engine oil samples

Sample Numbers	1	2	3	4
Free Water (abs/mm^2)	0	0	Significant	Significant

Table 6 Free water contents of gear oil samples

Sample Numbers	1	2	3	4	5	6
Free Water (abs/mm^2)	0.01	0.01	0.01	0.01	0.01	0.01

should be taken accordingly.

Oxidation is one of the most important parameters which must be tested in order to know actual condition of the oil as well as engine. The rate of oxidation of oil is accelerated by increase in temperature, water, acids and catalyst like copper. It is approximated that the lubricant life is reduced to half with 10°C increase in temperature. Also, the rate of oxidation increases gradually with time. Oxidation will lead to the formation of sludge and varnish as well as the increase in the viscosity [14]. Air is also responsible for the increase in oxidation of the oil. Air can be sucked into the system due to loose connections. When inside, there is plenty of agitation that allows the oxygen and hydrocarbons react. Gradual increase in the engine and gear oil oxidation with distance traversed are illustrated in Figure 3 and Figure 4, respectively. As observed from the figure, the oxidation of engine oil gradually increased over distance, however, it did not actually reach the upper permissible value. Therefore, based on the oxidation, immediate change of the engine oil is not required. On the other hand, in case of gear oil, it is observed that the last sample has exceeded the upper permissible value. This suggests the immediate change of the gear oil. The value might be increased and exceeded due to long term use. However, there is a possibility that the heat and air might have affected the oxidation of the gear oil. Therefore, it should be checked whether air control is maintained properly or not and the fittings should be checked for any defective seals. Proper grade oil should be used in this case, and also, the vibration should be kept minimum.

Acidity in oil can lead to corrosion of machine parts

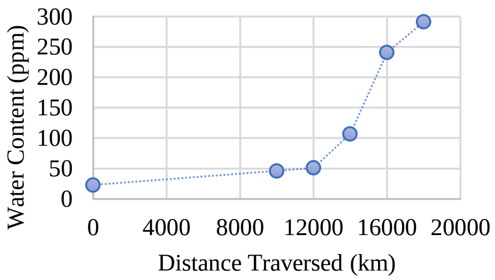

Fig. 2 Trends of dissolved water content for gear oil during the observed distance period of 18000 km.

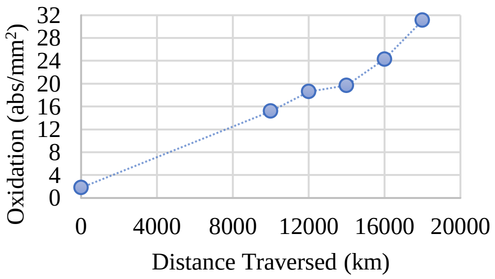

Fig. 4 Graphical representation of gear oil oxidation variation within the observation period.

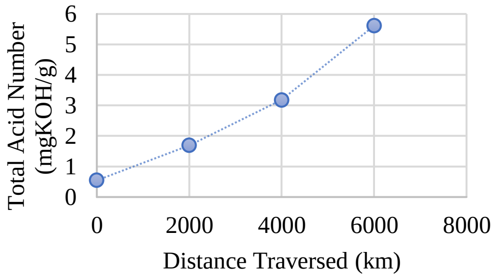

Fig. 5 Trends of acid number for engine oil during observation period of 6000 km.

and clogged oil filters due to the formation of varnish and sludge [12]. Amount of potassium hydroxide needed to neutralize one gram oil sample is its acid number [11]. Gradual change in total acid numbers of engine oil and gear oil samples are illustrated in Figure 5 and Figure 6, respectively. From the figure, it is observed that the TAN value of the fourth sample has exceeded the upper permissible value of the engine oil. Therefore, immediate change of engine oil is necessary. On the other hand, fifth and sixth gear oil samples have acid numbers which are out of range. Oil should have been changed immediately after fifth sample taking. Therefore, the duration between fifth and sixth samples was very unhealthy for the gearbox. However, no significant variation of slope of the curve for both engine and gear oil is observed and the values gradually increased over distance traversed. As there is no significant variation in slope for both engine and gear oil, the reason for high value of the last samples might be mainly due to the long duration of oil usage. However, maintenance steps are suggested for any breakdown prevention. As the TAN value is directly related to the oxidation and water content, the maintenance measures which were suggested during oxidation and water content analysis are also suggested here.

4.2 Viscosity Analysis

Viscosity is the most important parameter of the lubricating oil and must be considered during oil analysis. The lubricant must have very high viscosity index. Oil viscosity is affected by water, fuel entering oil, oxidation, soot, etc. Viscosity testing also provides rough picture about fuel dilution [12]. Though, it cannot give the clear picture, approximation can be made with the result as fuel dilution decreases the viscosity of oil at a considerable rate. Therefore, if there is sudden fall of viscosity then mechanical seals like cylinder and piston rings should be checked to see if there is any breakdown or worn surface which is the prime reasons for fuel dilution. Generally, viscosity at 40°C of the lubricant must be greater than or equal to 55 cSt and in no circumstances, it should not fall below 50 cSt [15].

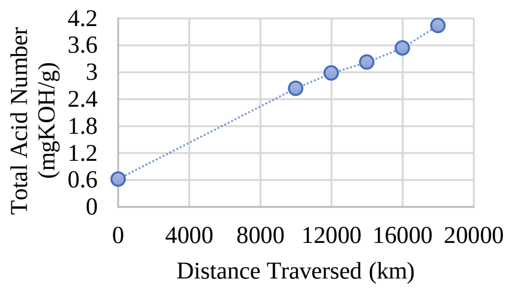

Fig. 6 Trends of acid number for gear oil during observation period of 18000 km.

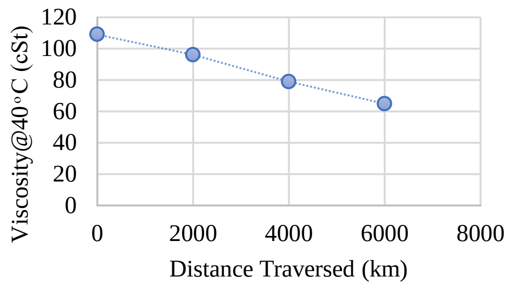

Fig. 7 Variation of viscosity of engine oil within the observed distance of 6000 km.

Variation of viscosities of engine and gear oil with traversed distance are presented in Figure 7 and Figure 8, respectively. It is observed from the figures that the viscosity of both oils decreased over distance traversed. However, the values finally did not reach the lower permissible level, i.e. 55 cSt. It is also observed that in both types of oil, there is no sudden fall of viscosity and the decreasing of viscosity was approximately uniform. Therefore, there is little possibility of fuel dilution. Here, in this case, the main reasons for gradual decreasing of viscosities are the usage of oil for long period of time and presence of water in the samples which were observed before.

From the oil analysis, it has been observed that, some parameters of engine and gear oils exceeded the range and suggested immediate change of oil. Table 7 and 8 show different parameters of engine and gear oil respectively, that were out of range and suggested oil change. In case of engine oil, it has been observed, both free water content and TAN value were out of range. But free water was found in significant amount at 4000 km, where TAN value exceeded at 6000 km. As, first change of oil was necessary at 4000 km, so the oil drain off was required after traversing 4000 km. On the other hand, from table 8, it has been observed, first gear oil change was necessary after traversing 16000 km due to high value of total acid number. Therefore, this method reliably suggests correct time for oil change in order to maintain good health of various parts.

Table 7 Exceeded values of engine oil parameters and their corresponding distances

Properties	Free Water	TAN
Alarming Values	Significant	5.61 mgKOH/g
Distance	4000 km	6000 km

meters and

ΓAN
3.54 KOH/g
)00 km

5. Conclusion

Condition monitoring using degradation and contamination analysis of engine and gear oil was done

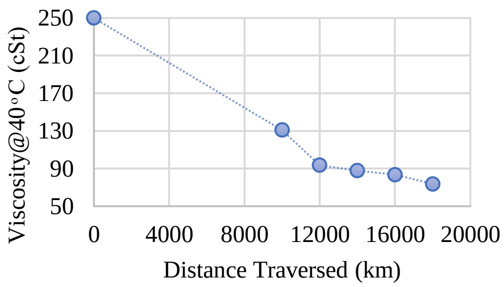

Fig. 8 Variation of viscosity of gear oil within the observed distance of 18000 km.

to achieve high reliability and maintenance decision in order to prevent sudden breakdown of engine and gearbox components. A regular moving truck was taken for observation. From the analysis, it was observed that bubbles and water content were in permissible range in both types of oils. Free water content of last two engine oil samples were significant. Viscosities of both oils were above the lower permissible value. Oxidation and TAN of gear oil suggested immediate change of oil. Acidity of last engine oil sample was also out of range. Based on the results, maintenance decisions need to be taken were discussed. Different properties like water content, oxidation, TAN, viscosity, etc. were measured in order to determine lubricant contamination and degradation using fluid scan. As viscosity is one of the main properties along with the other parameters like water content, oxidation, TAN, etc., the collective approach with fluid scan and viscotester can be a reliable condition monitoring technique of oil wetted machinery. Probable condition of the engine part and gearbox can be approximated by this technique. Exact condition will be known when those probable endangered parts are examined. To know the exact condition before examining components, different methods like Ferrography, SEM testing, etc. can be done. However, these are all time consuming and off-site methods and can be applied combined with fluid scan and viscotester in heavy industries and large powerplants, where it requires lot of time to overhaul the parts. However, for small sites, these off-site methods are not feasible as they require large instruments to carry out the tests and the examination of the automobile parts does not require lot of time. Therefore, with the combination of fluid scan and viscotester a very reliable on-site condition monitoring of automobile is possible and proper maintenance decisions can be taken to prevent sudden failure of components.

6. References

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Acronyms

IC	Internal Combustion
FTIR	Fourier Transform Infrared
NDT	Nondestructive Testing
TAN	Total Acid Number
SEM	Scanning Electron Microscope
ASTM	American Society for Testing and Materials